NTHMP Workshop

"Volcanic tsunamis" : cases studies of Anak Krakatau 2018 and hypothetical CVV collapses

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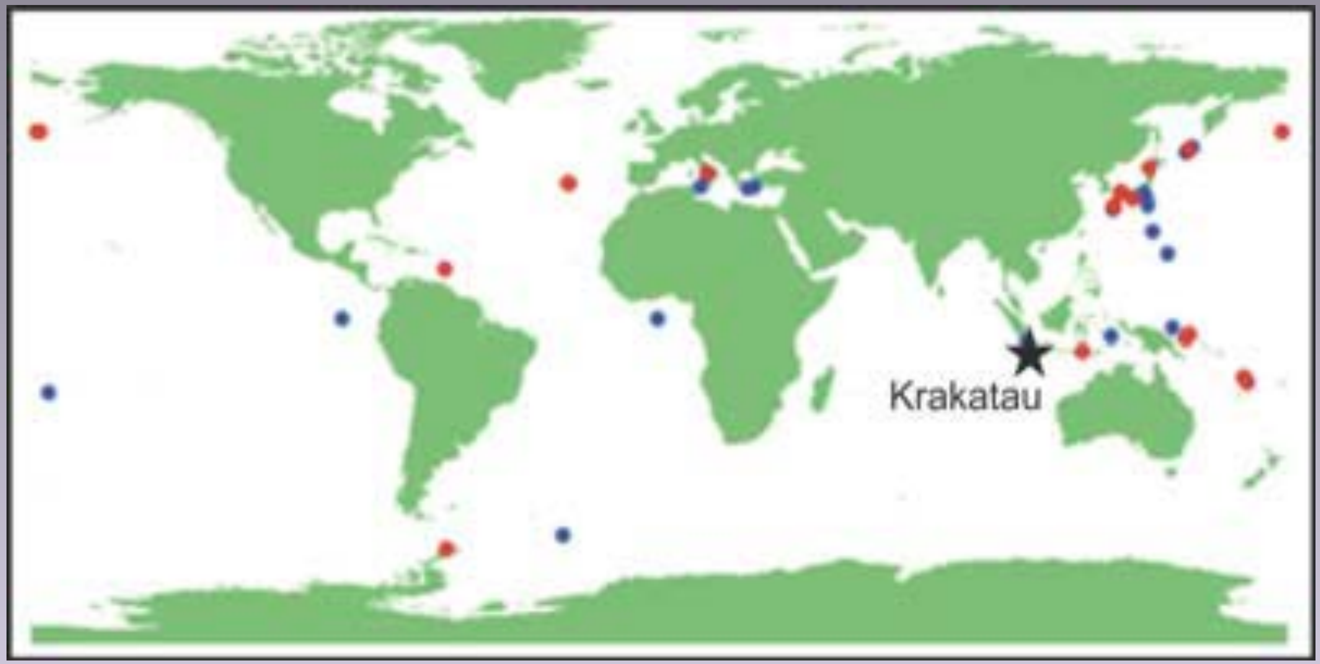
[NSF: CMMI-15-35568, GEO-17-56665; NERC: NE/S003509/1; NTHMP…]

Caldera forming volcanoes



-> (red circles) Calderas within 5 km of the coast
-> (blue circles) Submarine calderas.

Krakatau 1883

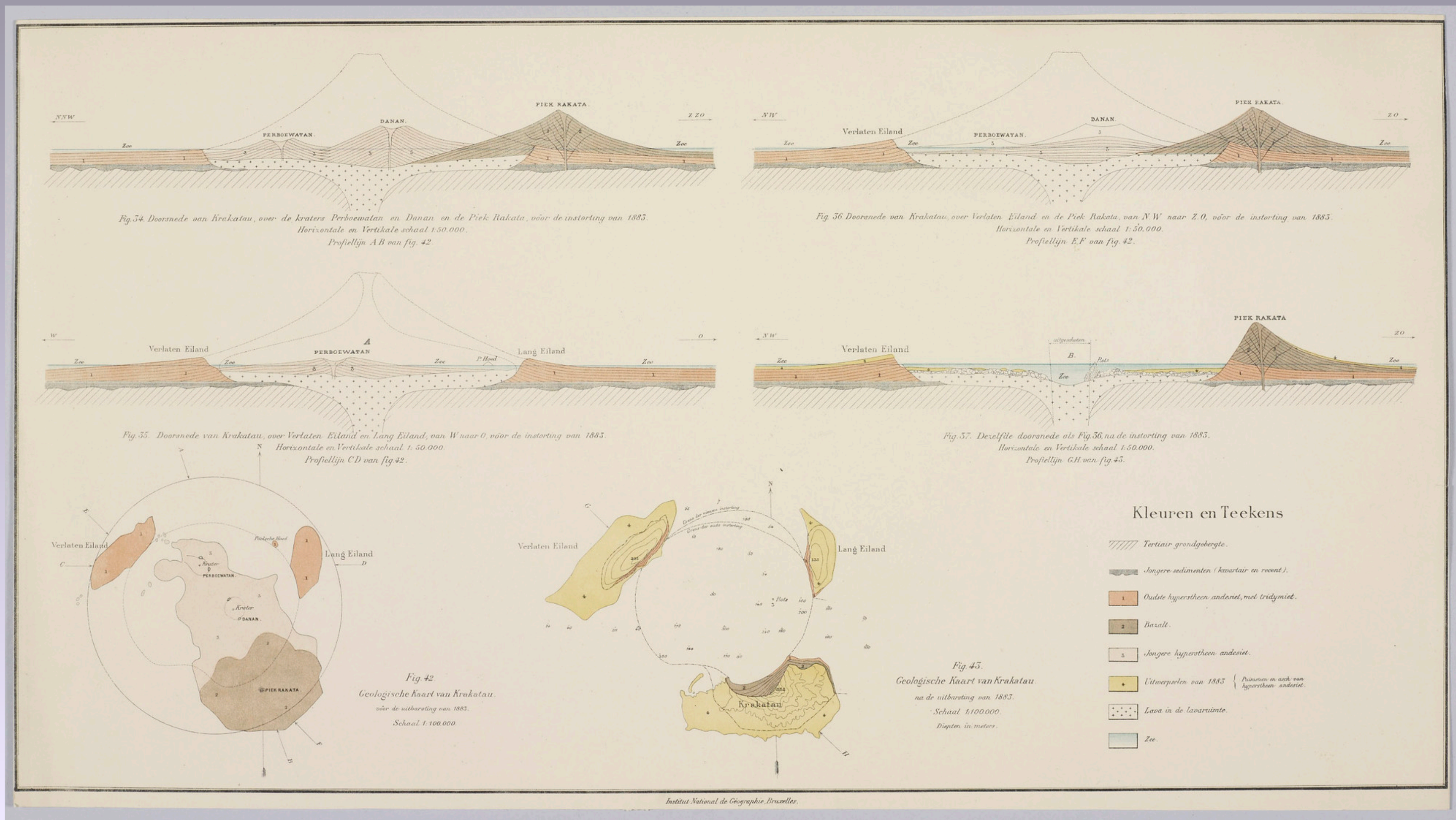
Krakatau 1883

- Pre-eruption

- During eruption (before tsunami)

Krakatau 1883

Verbeek, R. D. M. *Krakatau*. Government Press Batavia (1885).
Verbeek, R. D. M. The Krakatoa Eruption. *Nature* **30**, 10-15 (11 May 1884)



Krakatau 1883

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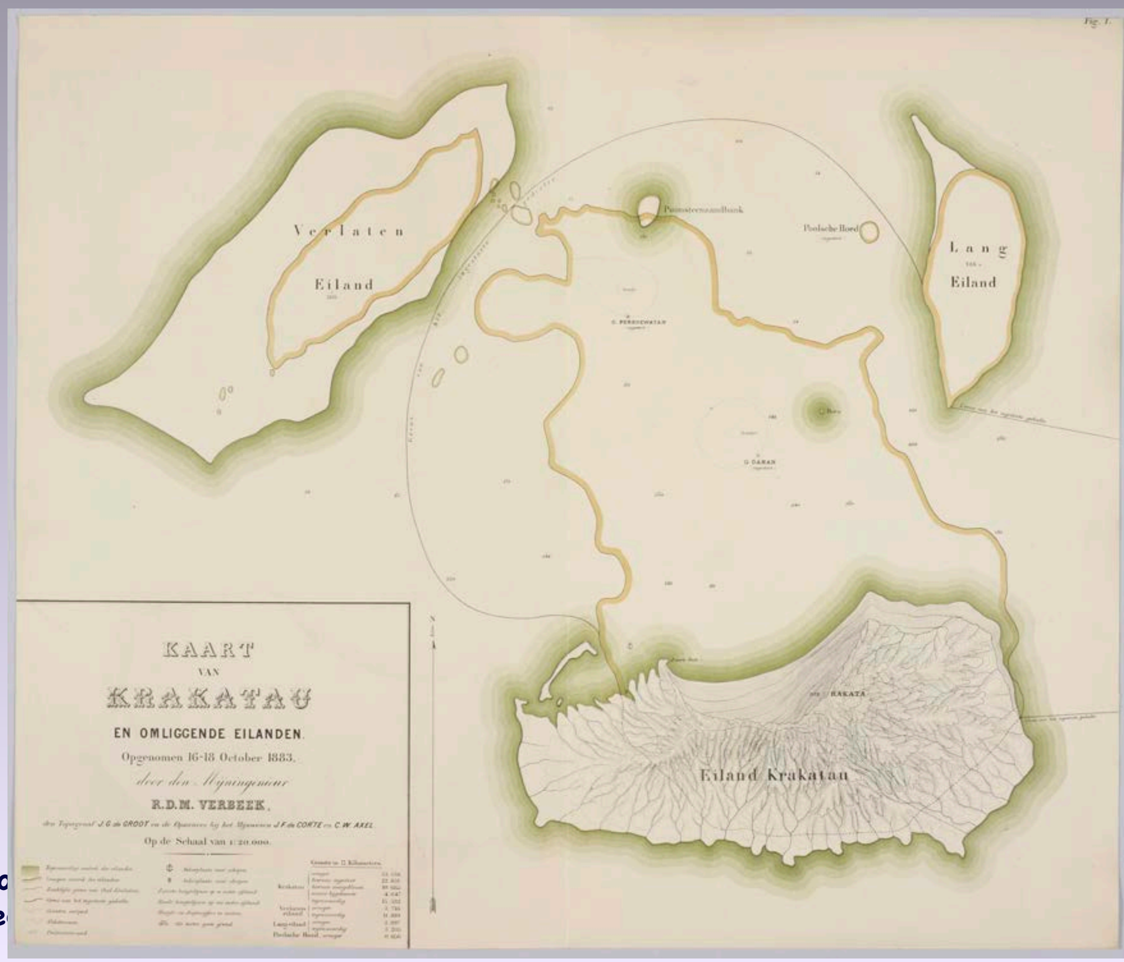
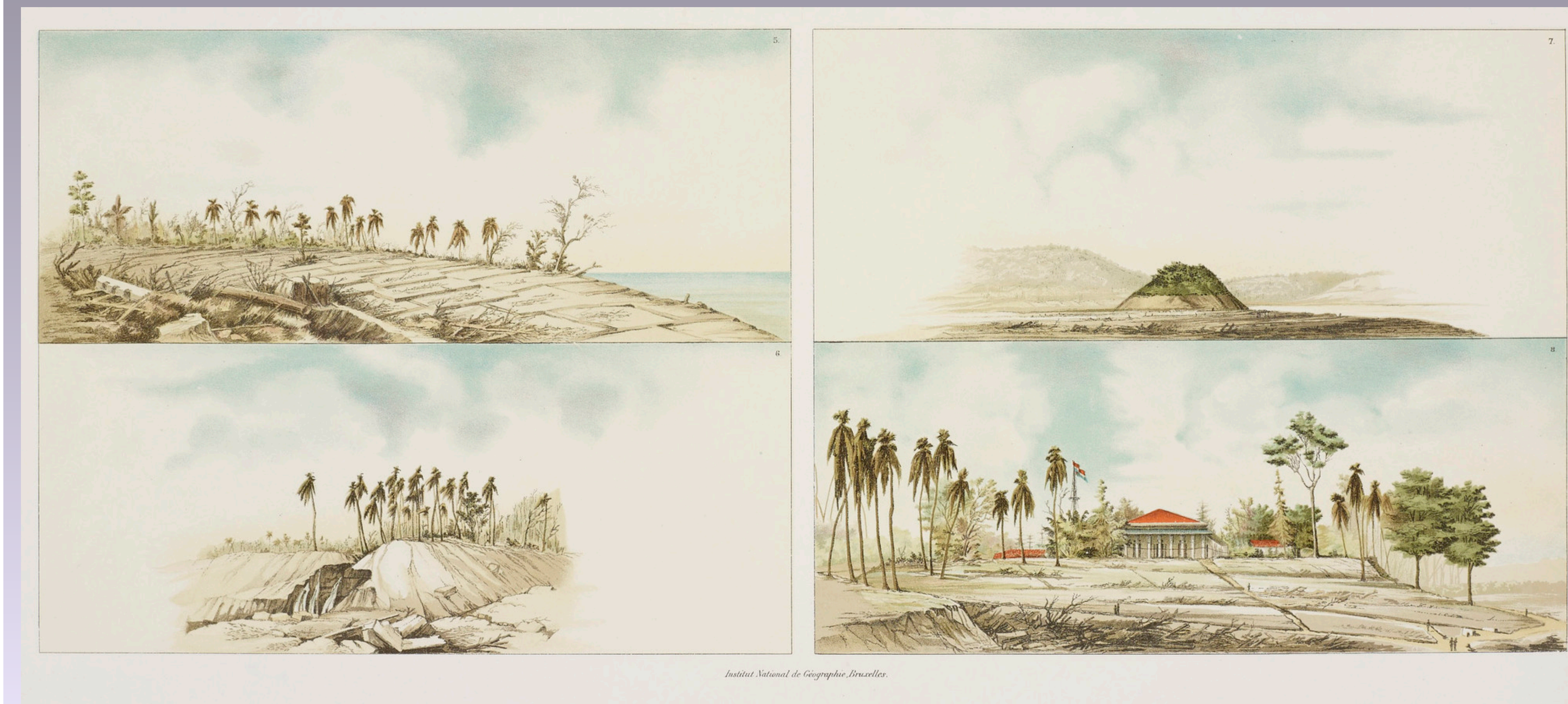


Krakatau 1883

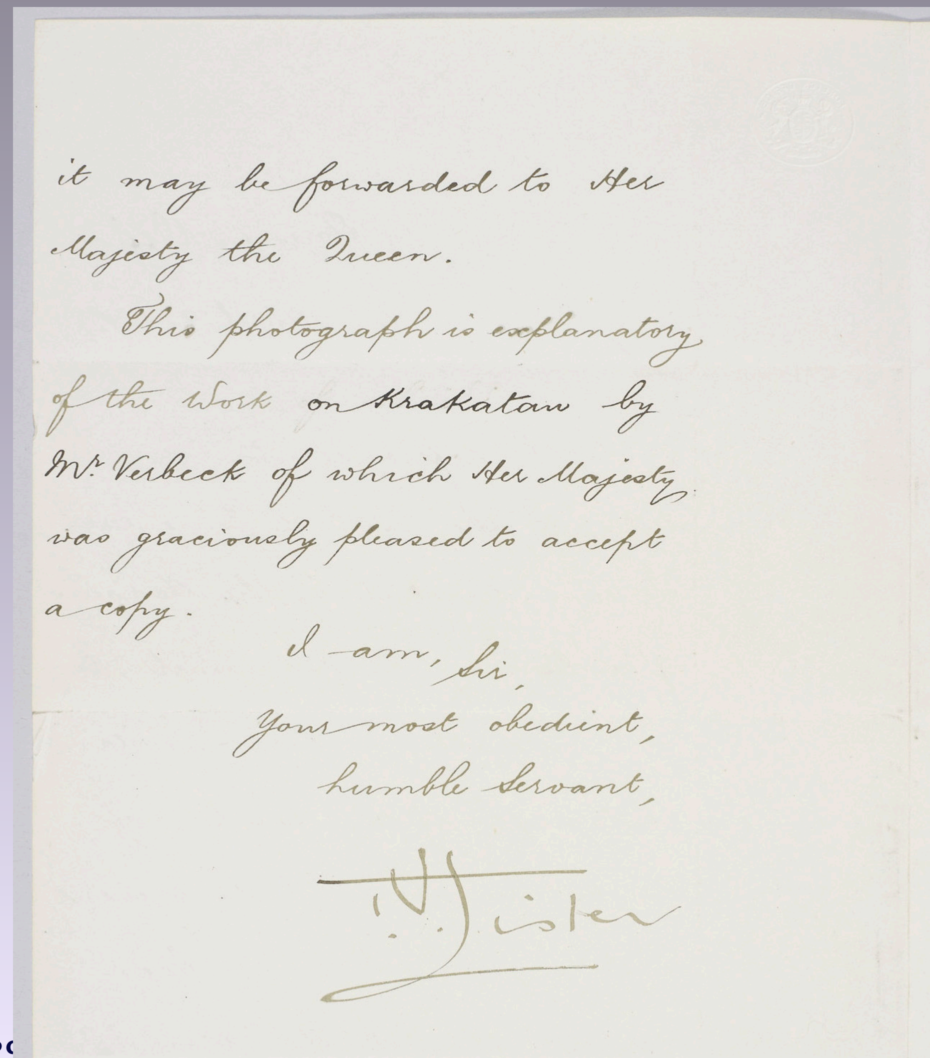
Verbeek, R. D. M. *Krakatau.* Government Press Batavia (1885).

Verbeek, R. D. M. The Krakatoa Eruption. *Nature* **30**, 10-15 (11 May 1884)



Krakatau 1883

Wharton, W. J. L. in *The Eruption of Krakatoa, and Subsequent Phenomena, Report of the Krakatoa Committee of the Royal Society, London* (ed G. J. Symons) 494 (The Royal Society, 1888).


it may be forwarded to Her Majesty the Queen.

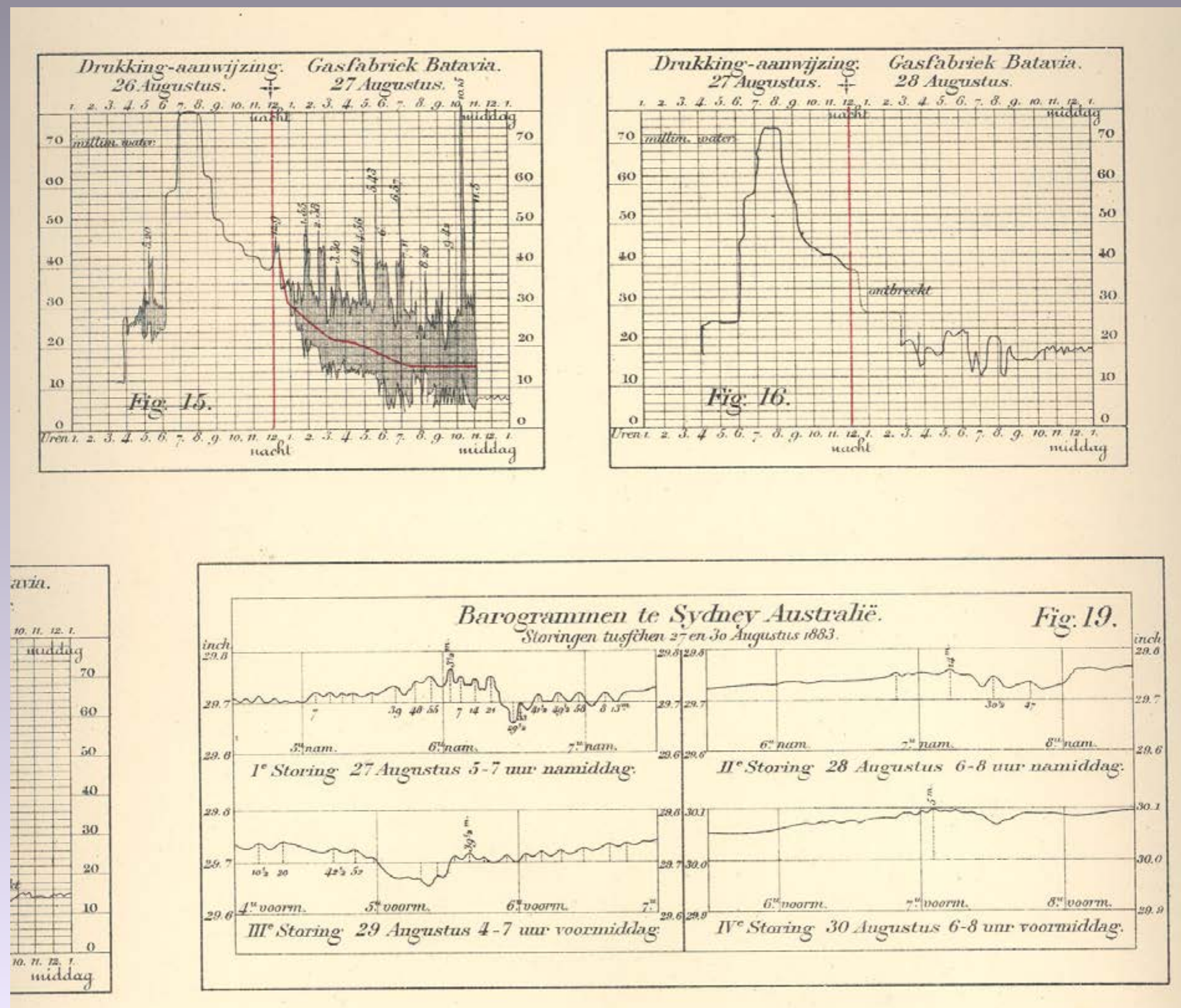
This photograph is explanatory of the work on Krakatau by Mr Verbeck of which Her Majesty was graciously pleased to accept a copy.

I am, Sir,
Your most obedient,
humble servant,

Krakatau 1883

Verbeek, R. D. M. The Krakatoa Eruption. *Nature* **30**, 10-15 (11 May 1884), doi: 10.1038/030010a0.

-> Runup measurements



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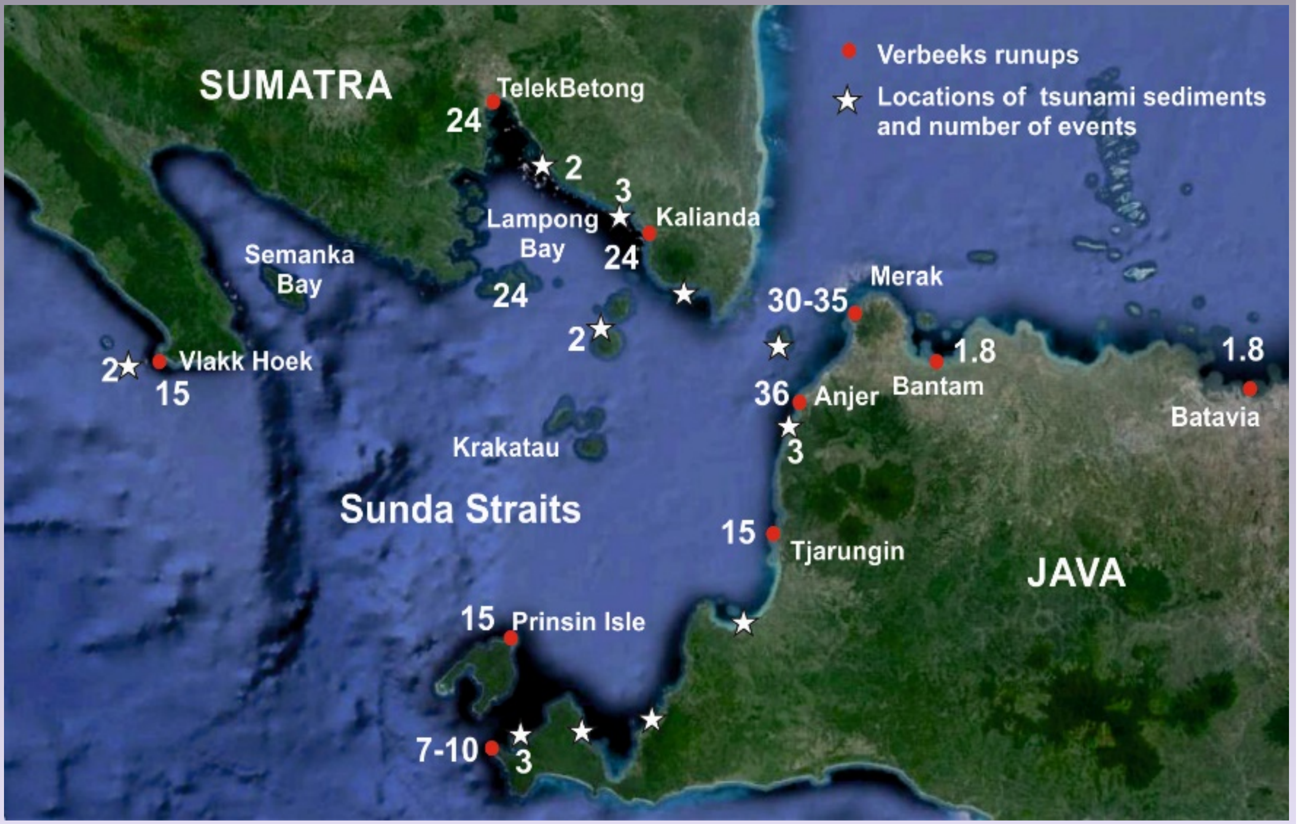
Krakatau 1883

Verbeek, R. D. M. The Krakatoa Eruption. *Nature* **30**, 10-15 (11 May 1884), doi:10.1038/030010a0.

-> Major tsunami (killed 33,000 people)
-> Runup meas. (m) (up to 36 m)
-> Tsunami deposits
-> Batavia tide gauge (leading elevation w.)



Krakatau 1883

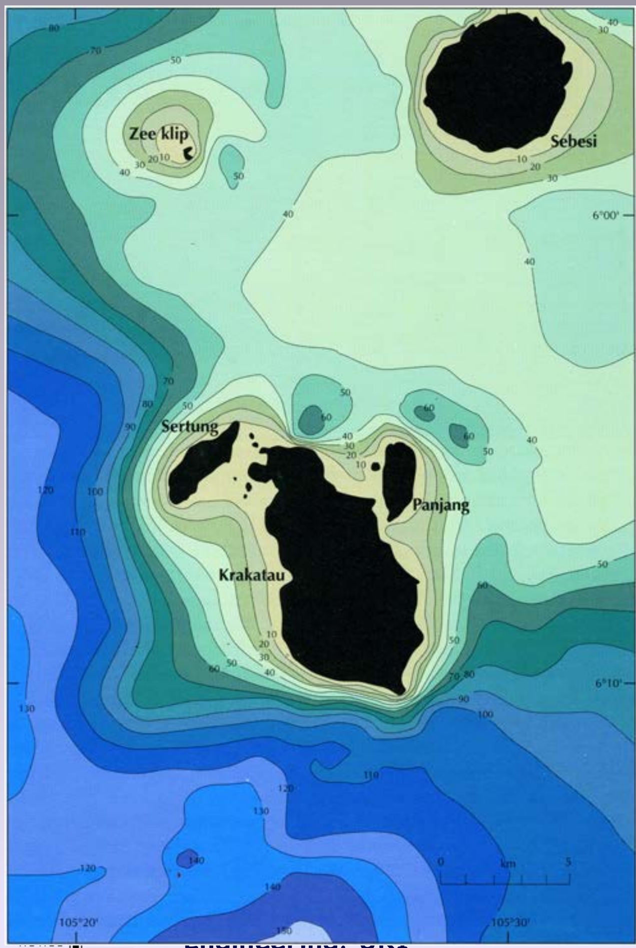
-> 130 years of work to explain eruption and tsunami generation mechanisms => It is still not clear what the main mechanism was

- …
- Sigurdsson, H., S. Carey, C. Mandeville & Bronto, S. Pyroclastic flows of the 1883 Krakatau eruption. *Eos Trans. AGU* **72**(36), 377, 380–381 (1991).
- Sigurdsson, H., Carey, S. & Mandeville, C. Submarine pyroclastic flows of the 1883 eruption of Krakatau volcano. *National Geographic Res.* **7**, 310-327 (1991).
- Mandeville, C. W., Carey, S., Sigurdsson, H. & King, J. Paleomagnetic evidence for high-temperature emplacement of the 1883 subaqueous pyroclastic flows from Krakatau Volcano, Indonesia. *J. Geophys. Res.: Solid Earth* **99**, 9487-9504 (1994).
- Stroker, K. *Investigation of Submarine Deposits from the 1883 Eruption of Krakatau, Indonesia Based on Sub-bottom Profiling* Masters thesis, University of Rhode Island, (2003).
- Many others ….

-> Pyroclastic flows/PDC deposits measurements and mapping (m)

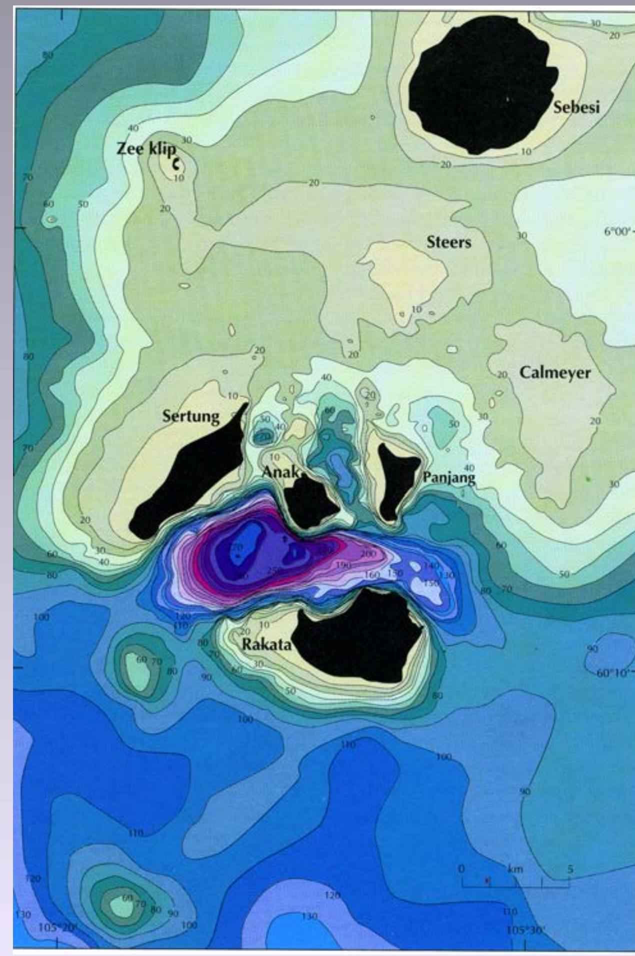
Krakatau 1883

-> Pyroclastic flows/PDC deposits measurements and mapping (m)



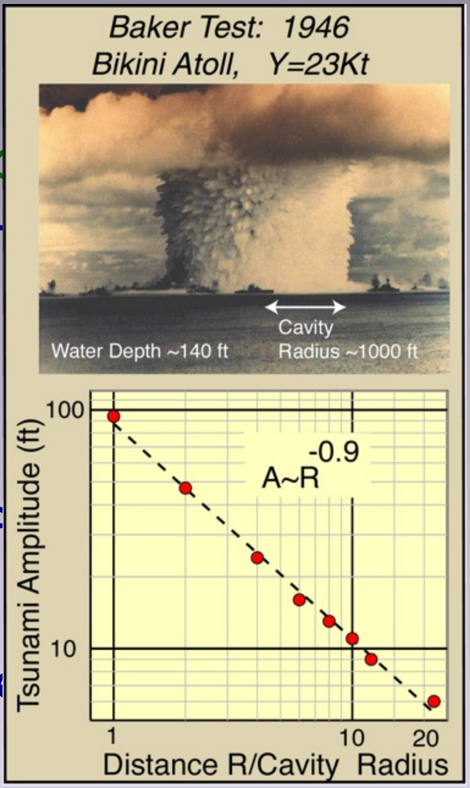
<- Before

After ->
(250 m deep caldera)



Krakatau 1883

-> Tsunami generation mechanisms:



- Pyroclastic Flows (PFs) "lava"/Pyroclastic density c
  - Dense PF/PDC => subaerial landside tsunami gen
  - Light PF/PDC => Float and act as wavemakers
  - Hot PF/PDC => small local thermal explosions
    (subaerial PDCs is *likely leading mechanism*)
- Caldera formation ("collapse of volcano onto itself
  - creates major lateral piston motion
    (*leading depression* w. but lead. elevation w. obse
- Explosions
  - pressure shock wave acts on free surface causing waves
    (*shock wave is too fast to generate tsunamis => Bikini*)

Bikini 1946

-> Preliminary Tsunami generation simulations:

- Using "Tsunami Square"

(S. Ward) => Simulated nuclear shock wave

Krakatau 1883

-> Preliminary Tsunami generation simulations:

- Using “Tsunami Square” (S. Ward) => caldera-piston motion

Krakatau 1883

-> Preliminary Tsunami generation simulations:

- Using "Tsunami Square" (S. Ward) => caldera-piston motion
- Leading *depression* w.

Krakatau 1883

-> Preliminary Tsunami generation simulations:

- Using "Tsunami Square" (S. Ward) => Pressure wave

Krakatau 1883

-> Preliminary Tsunami generation simulations:

- Using NHWAVE and FUNWAVE (Grilli et al.) => PDC generation

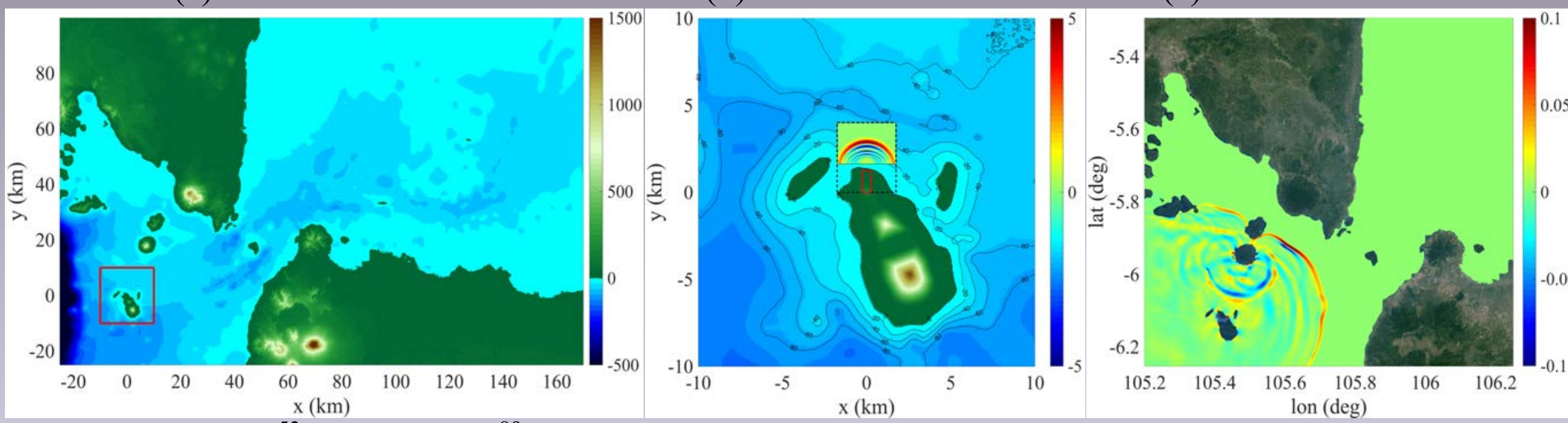
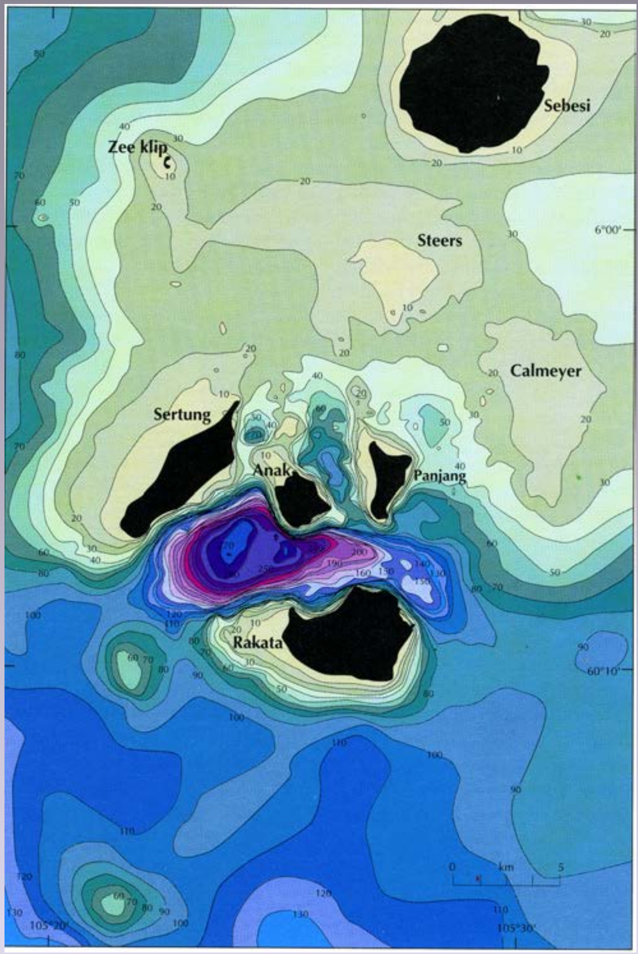


Fig. 7 NHWAVE[53]-FUNWAVE[89] simulation of tsunami generation and propagation, by a small PDC flow (500 m wide by 20 m thick) entering the water at 53 m/s (~$10^7 m^3/s$ for entire perimeter), over a 6 deg. slope. (a) 100 m resolution FUNWAVE grid, with pre-eruption bathy/topo (color scale in meter) and red box around Krakatau; (b) zoom into red box, NHWAVE 5 m grid is smaller domain with initial wave generation (color scale in meter); (c) tsunami propagation in FUNWAVE after 25 min (scale in m).

=> NSF project (18/21): new surveys and simulations -> mechanism ?

Anak Krakatau 2018

-> Deep caldera (250 m) formed in 1883
-> 1927: Anak Krakatau emerged (9 m)
1933: AK culminates at 67 m
1960: AK culminates at 138 m
1992: AK culminates at 250 m
2018: AK culminates at 330 m
12/22/18 at 16:28 local time:



-> On-off AK eruption since June 2018

Anak Krakatau 2018

-> Erupting AK drone footage on 10/24/2018

Anak Krakatau 2018

-> Deep caldera (250 m) formed in 1883

-> 1927: Anak Krakatau emerged (9 m)

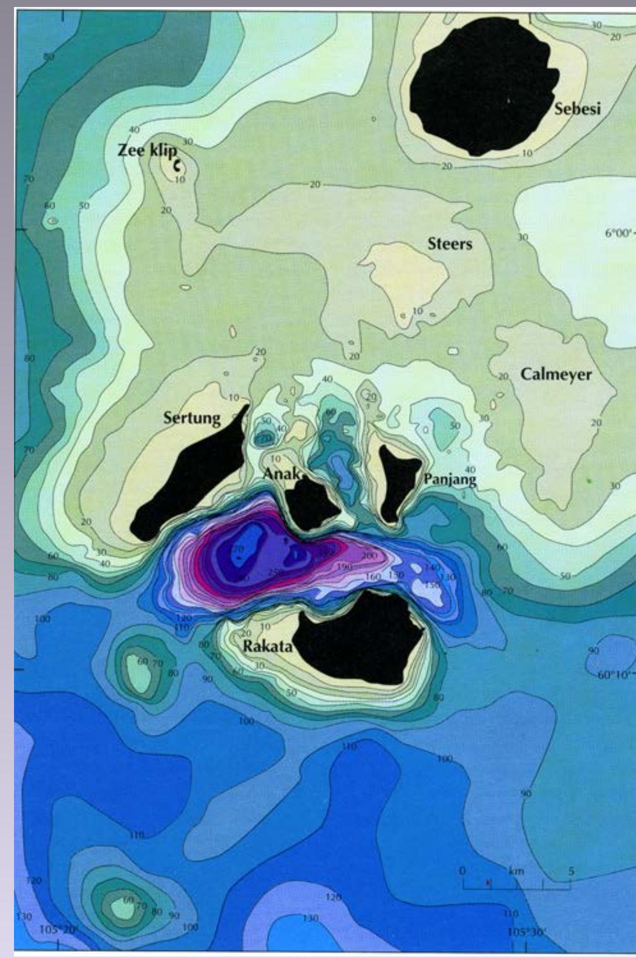
1933: AK culminates at 67 m

1960: AK culminates at 138 m

1992: AK culminates at 250 m

2018: AK culminates at 330 m

12/22/18 at 18:56 local time:

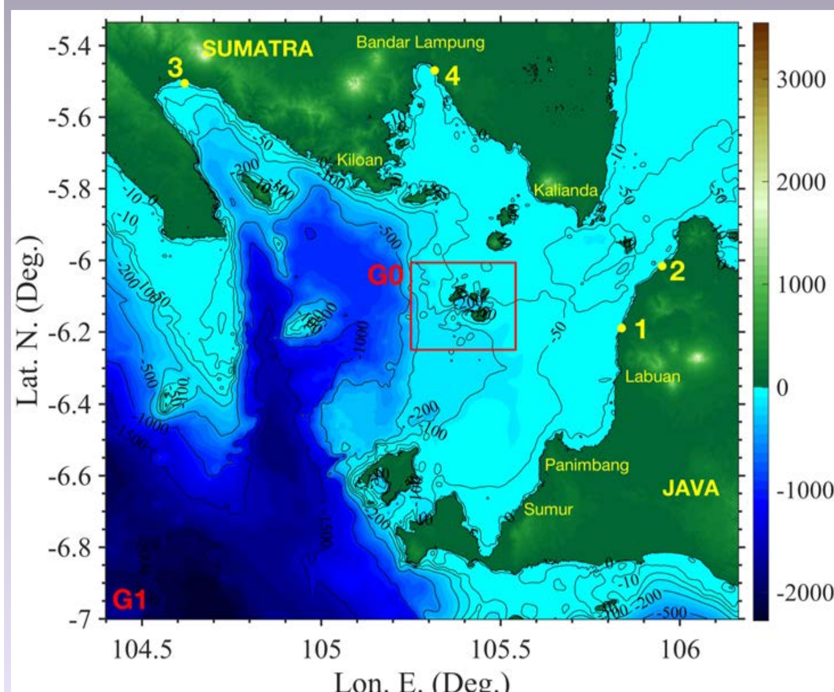


-> Major tsunami impacts Java at 21:30 local time

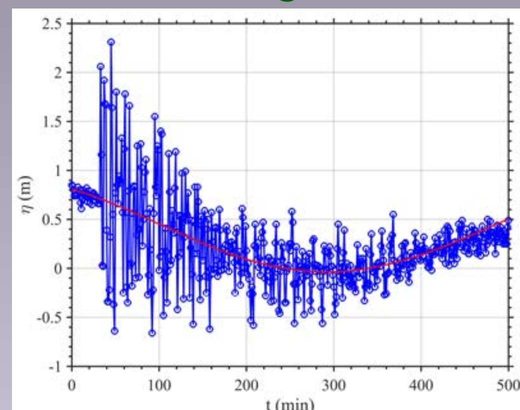
Anak Krakatau 2018

-> Major tsunami impacts Java at 21:30 local time

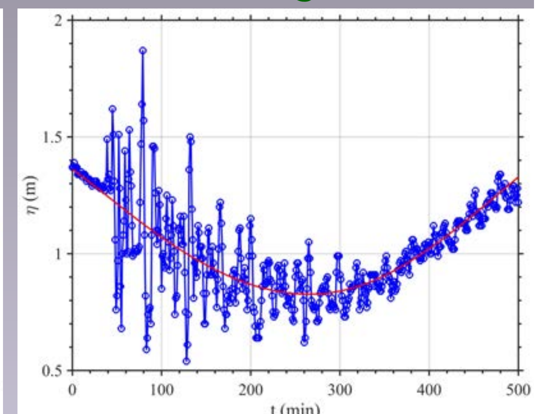
- Tide gauge observations
- t = 0 is 20:57 local
- Seismographs 20:55-57

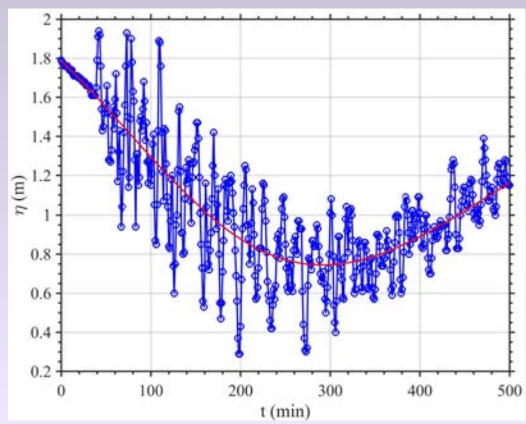


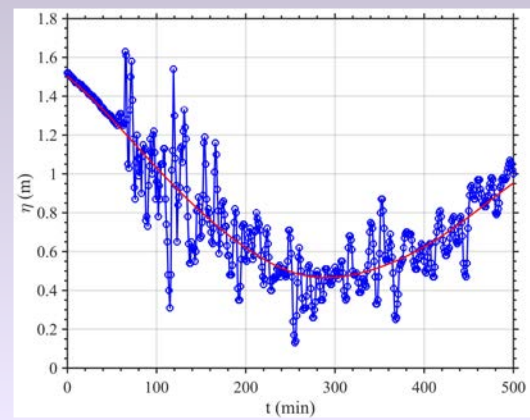
Gauge 1



Gauge 2







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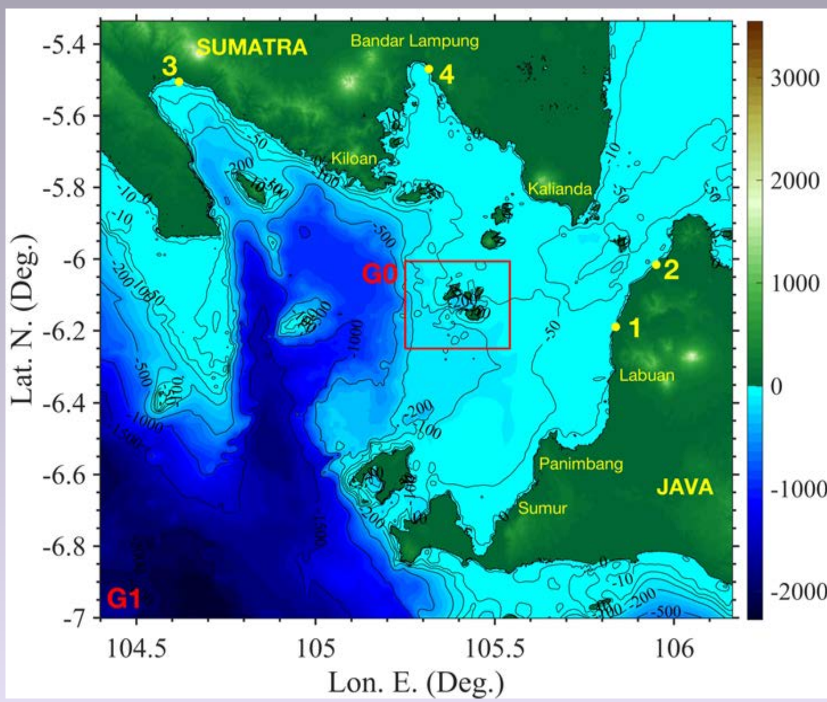
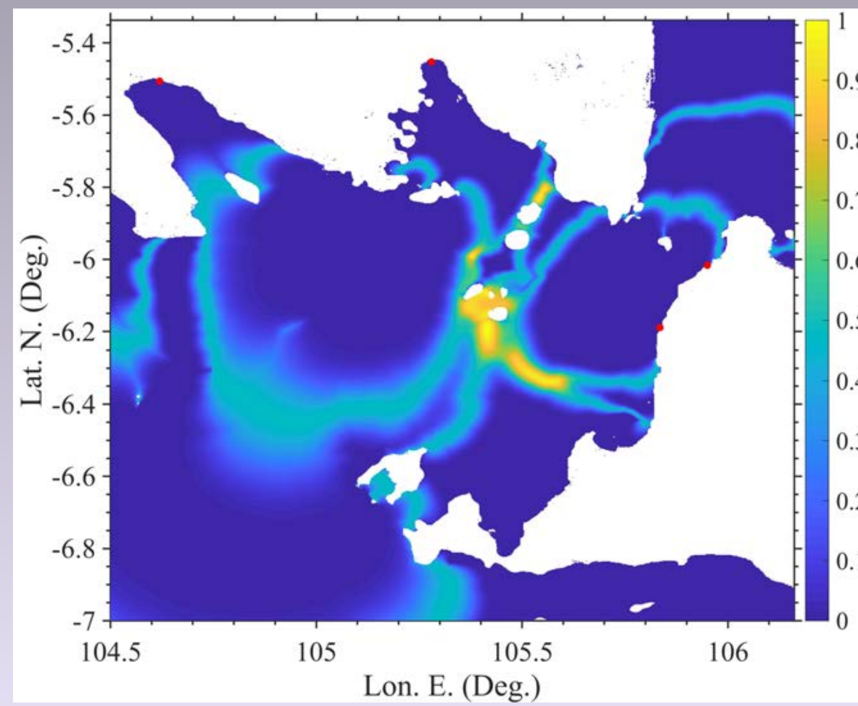
Anak Krakatau 2018

-> Major tsunami impacts Java at 21:30 local time

- Tide gauge observations
- t = 0 is 20:57 local

Inverse ray tracing analysis
(7′ waves; Gaussian uncertainty, 90s s.d.)

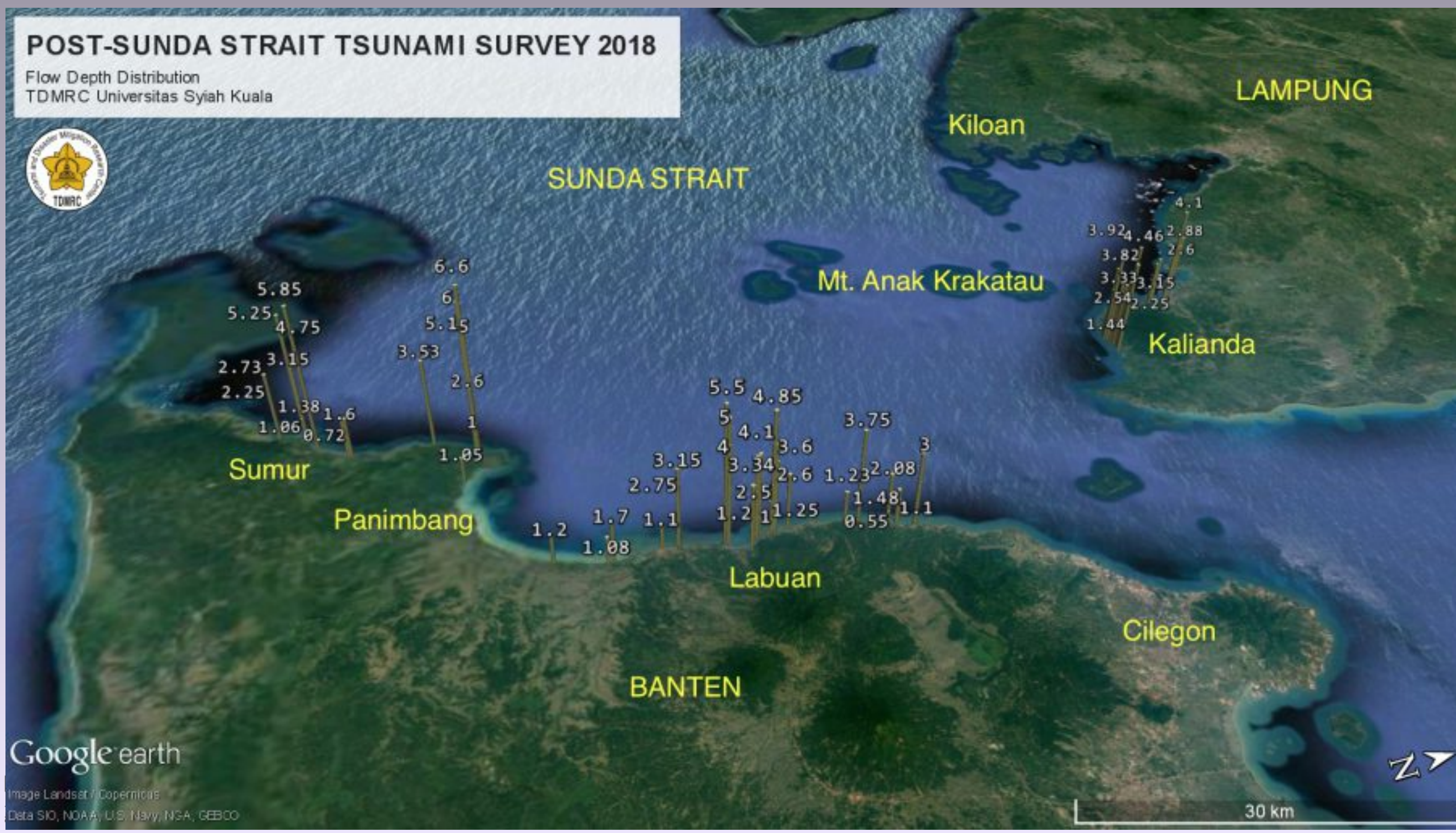




Anak Krakatau 2018

-> Major tsunami impacts Java at 21:30 local time

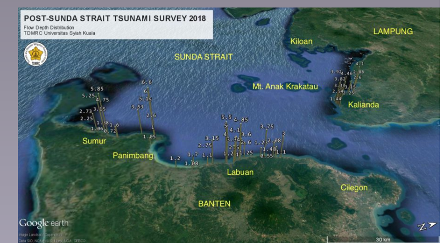
- TDMRC field survey (01/02/2019) (4-6 m flow depth R up to 13 m)

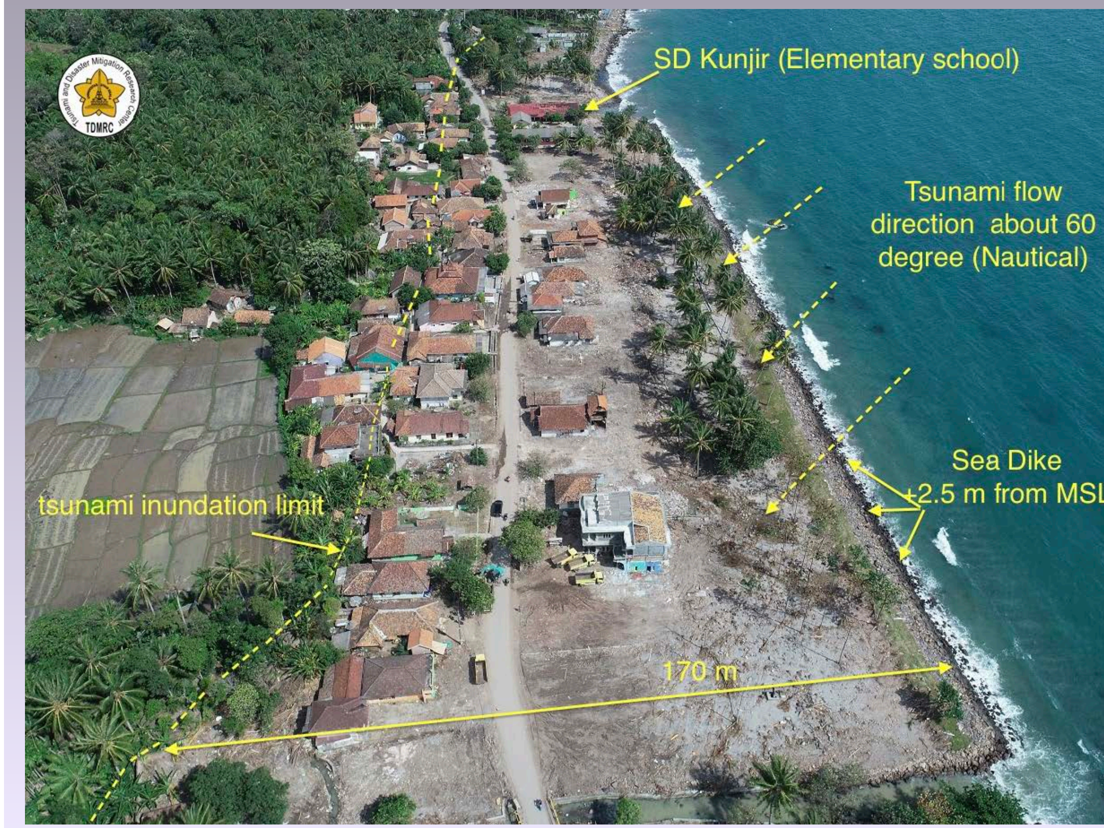


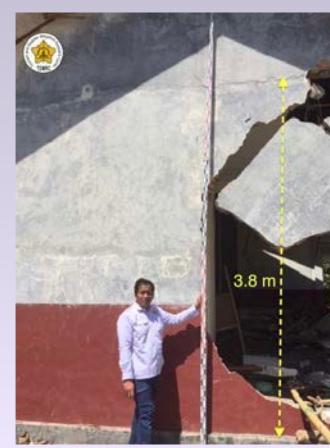
Anak Krakatau 2018

-> Major tsunami impacts Java at 21:30 local time

- At least 430 reported fatalities and many missing
- Kalianda area:



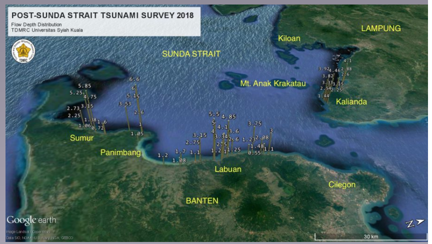




Anak Krakatau 2018

-> Major tsunami impacts Java at 21:30 local time

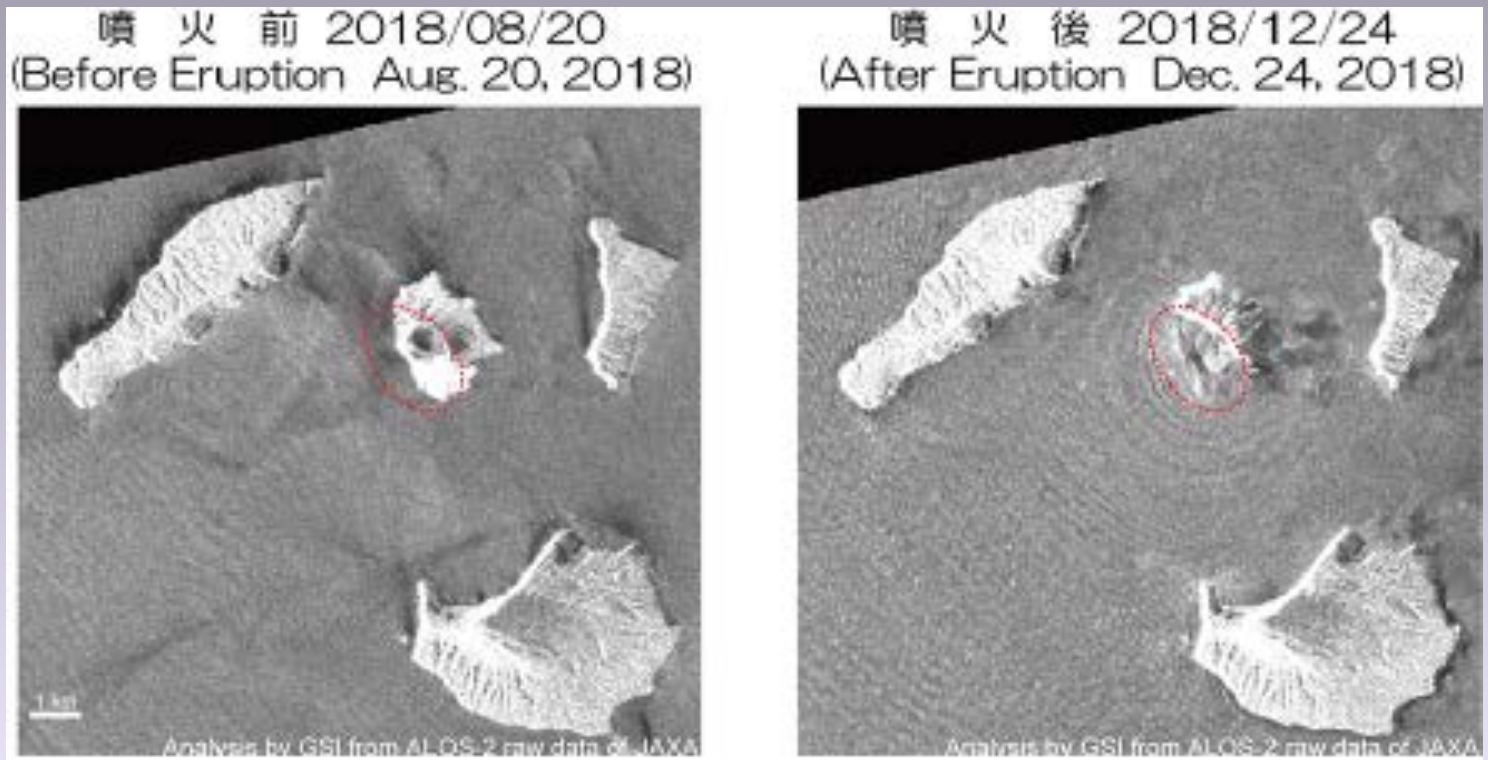
- At least 430 reported fatalities and many missing
- Carita-Anyer (Labuan) area (NY Times 12/23/18):



Anak Krakatau 2018

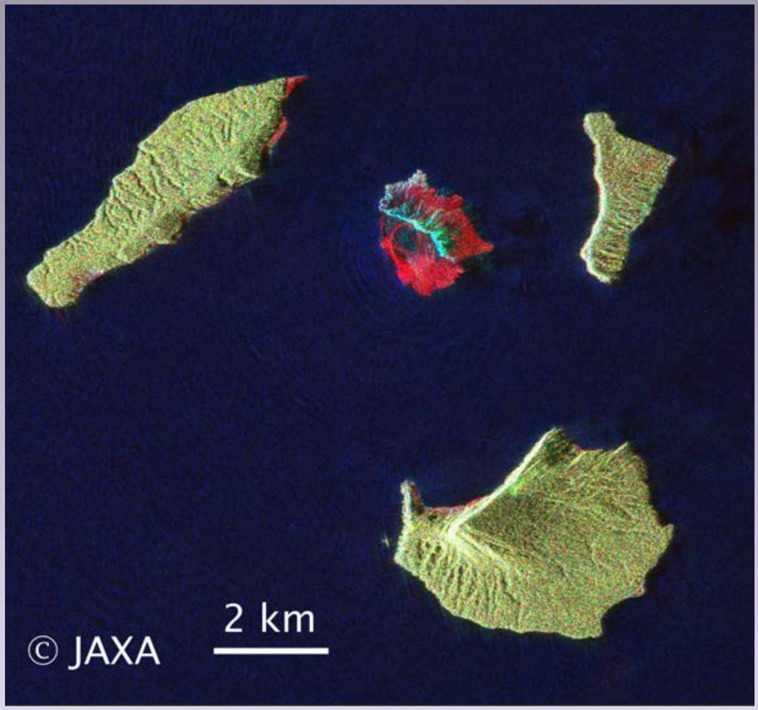
-> Evidence of sector flank collapse of Anak Krakatau (radar, satellite images, video/drones,…)

- Geomorphic change observed by Sentinel-1a SAR on 12/24/18

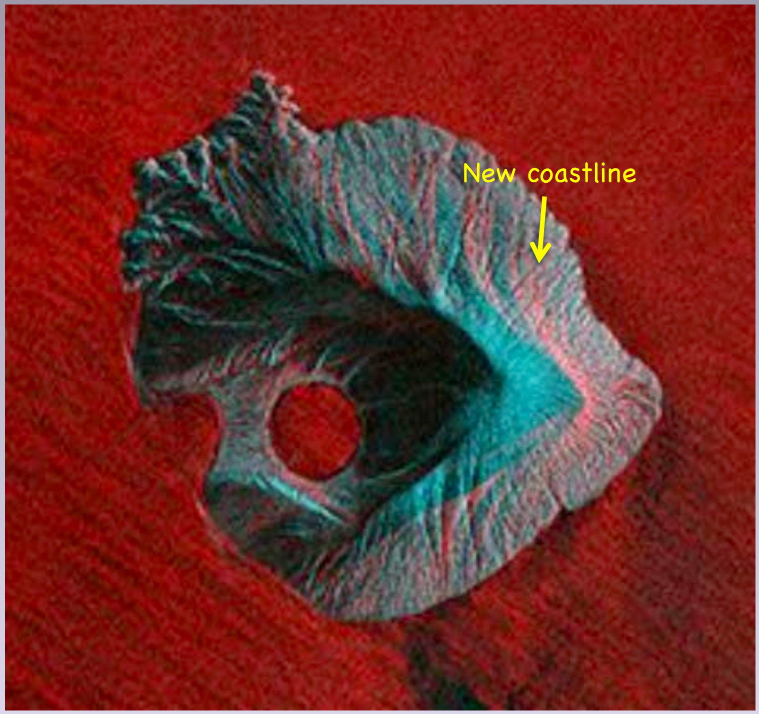


Anak Krakatau 2018

-> Sector flank collapse of Anak Krakatau (radar, satellite images, video/drones,…) + subsequent Surtseyan phreatomagmatic activity



Polarimetric color-composite image on 12/24/18

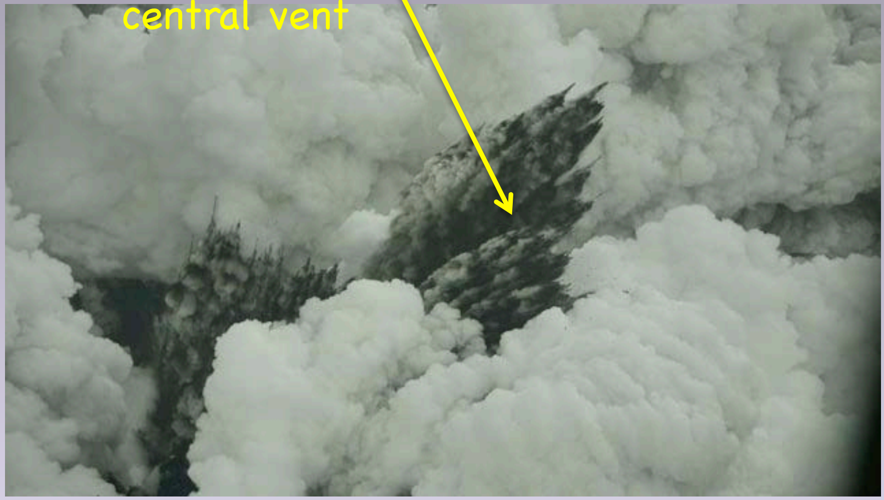


Iceye radar image on 01/09/19

Anak Krakatau 2018

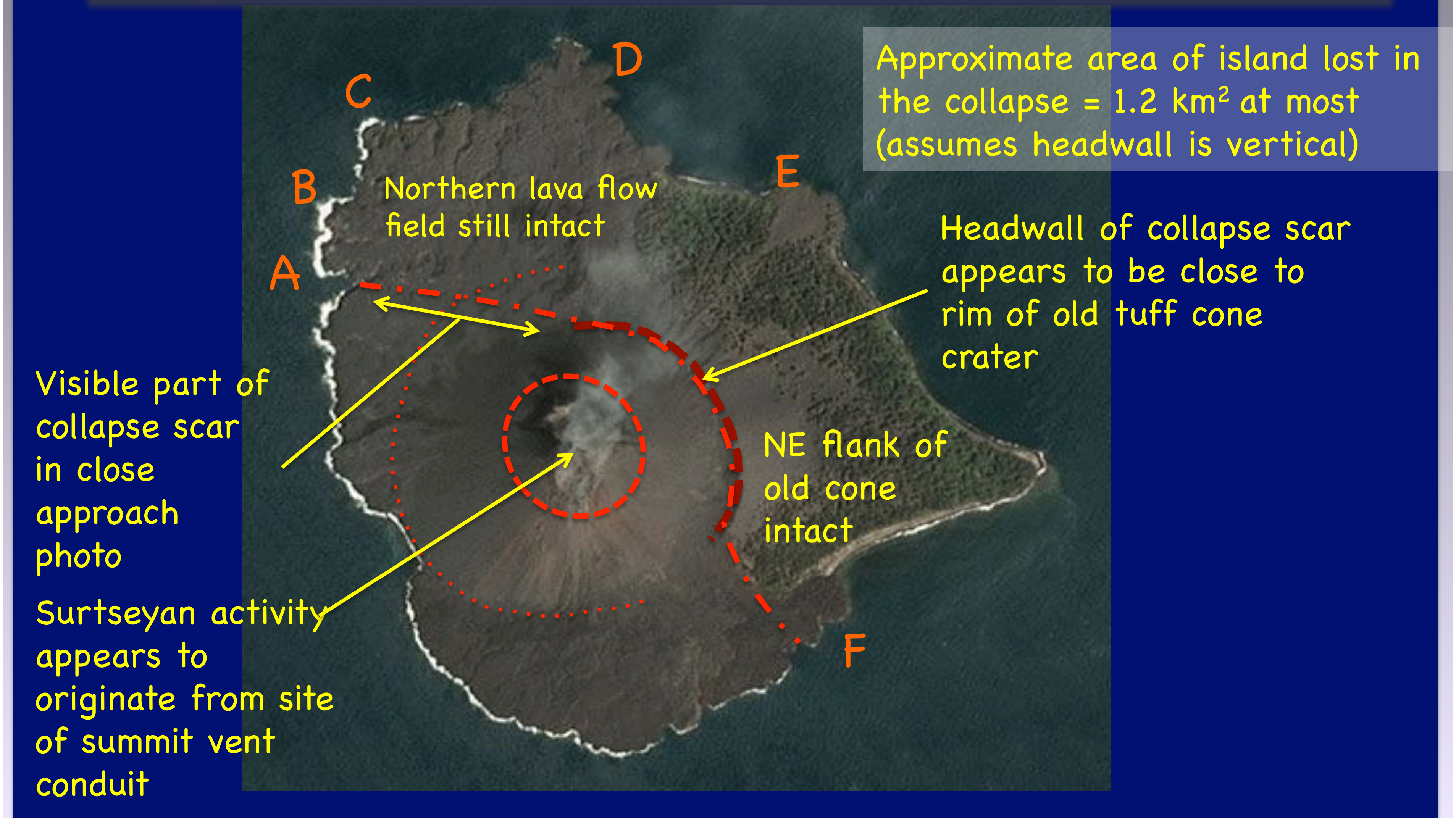
-> Sector flank collapse of Anak Krakatau (radar, satellite images, video/drones,…) + subsequent Surtseyan phreatomagmatic activity

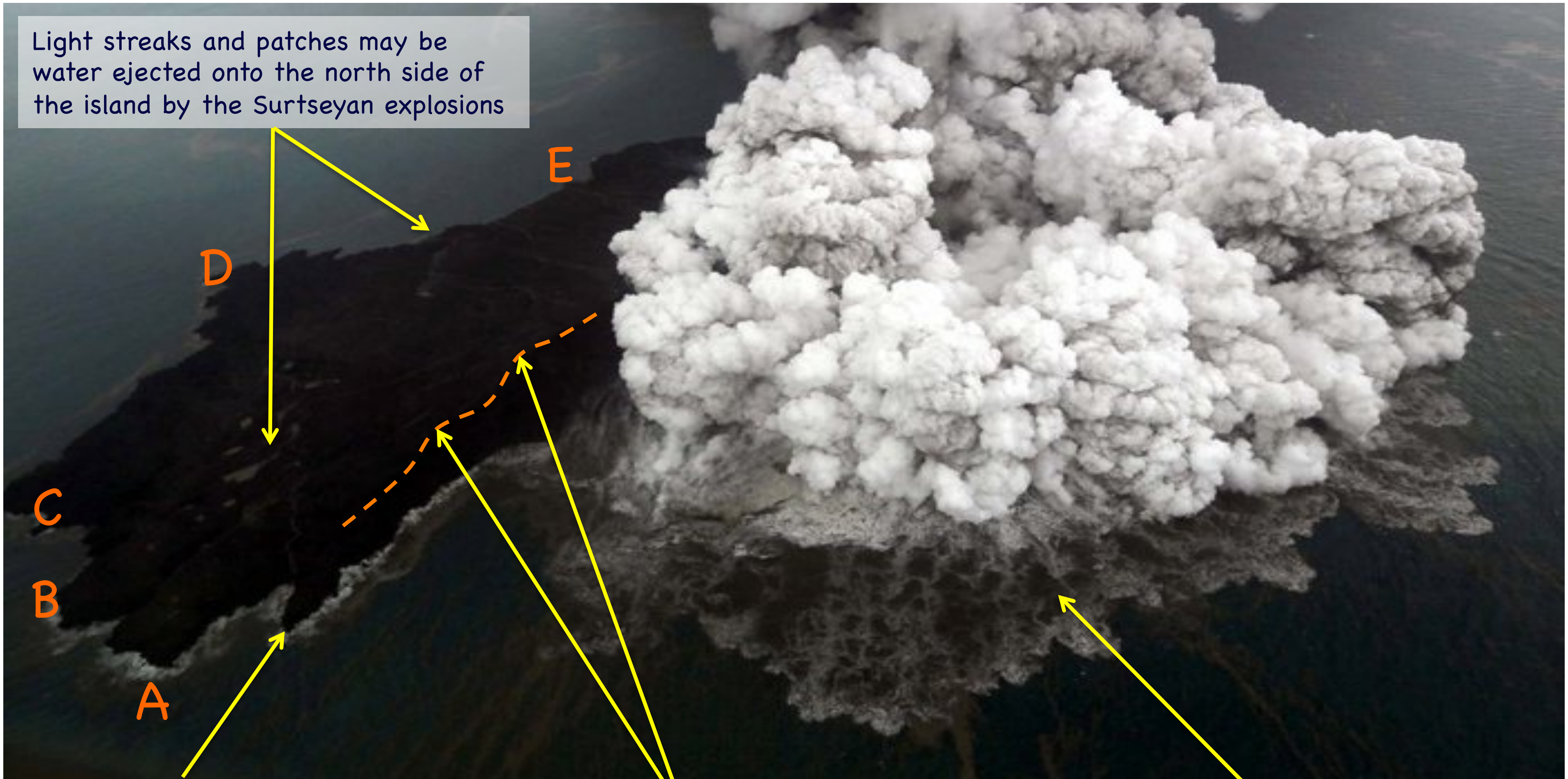
Dicky Adam picture on 12/23/18
(Sisiq flyover)



Dicky Adam picture on 12/23/18
(Sisiq flyover)

Inferred plan view geometry of the subaerial part of the collapse scar at time of Sisiq flyover on 23rd December





This crag is only feature disappearing between 23rd December and the photos of 30th December and later

Scallop features along the northern scarp of the collapse seem to persist into later images, suggesting little instability and retreat of the scarp after 23rd December

Pumice floating on the sea surface may increase backscatter intensity in the radar images

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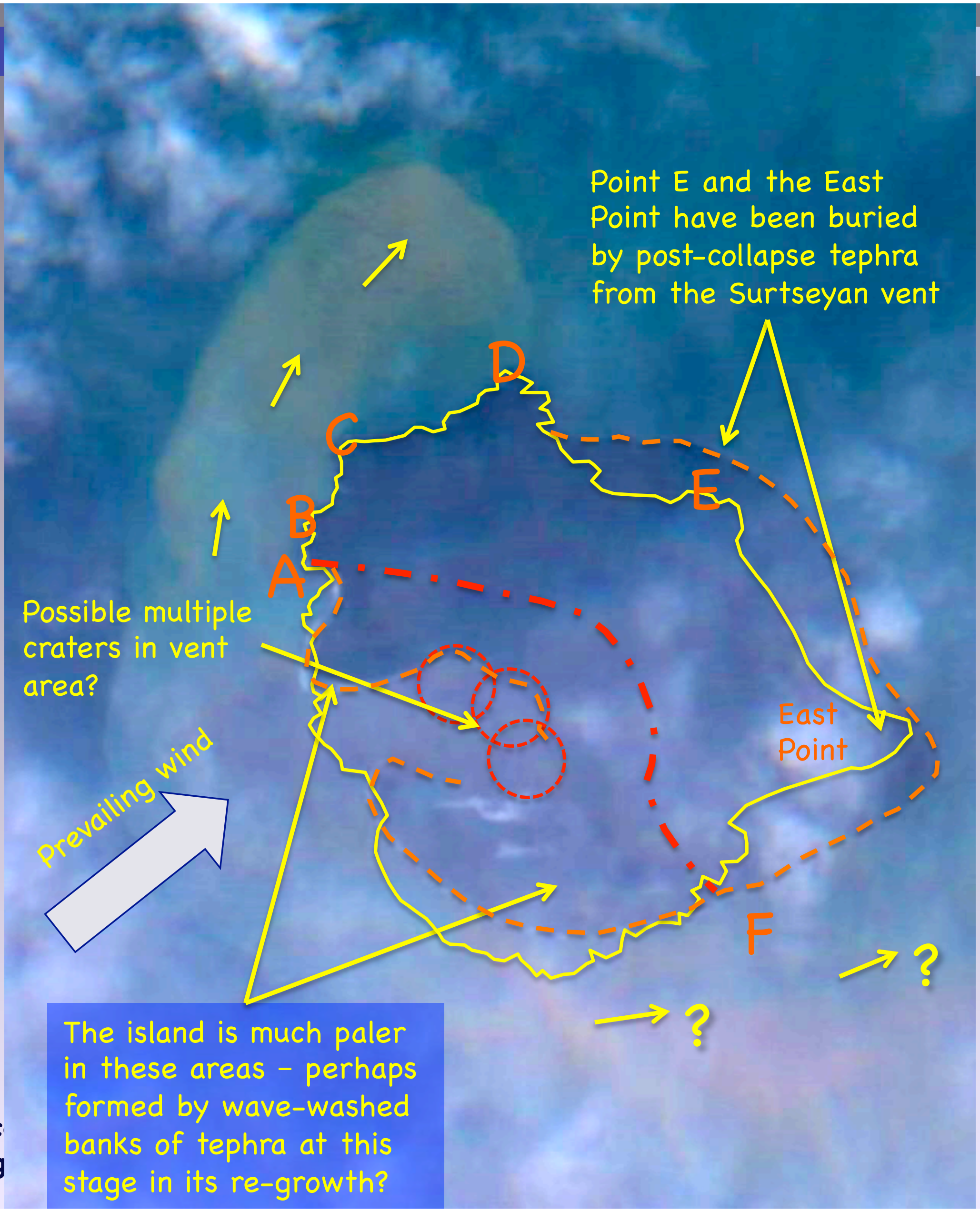
Sentinel image from Dec 29th

Short yellow arrows indicate inferred motion of sediment plumes



The "vent area" is indicated by:

(i) The white mottled plume extending to the NE and E in this image

(ii) the apparent embayment in this image and in the 26th December radar image

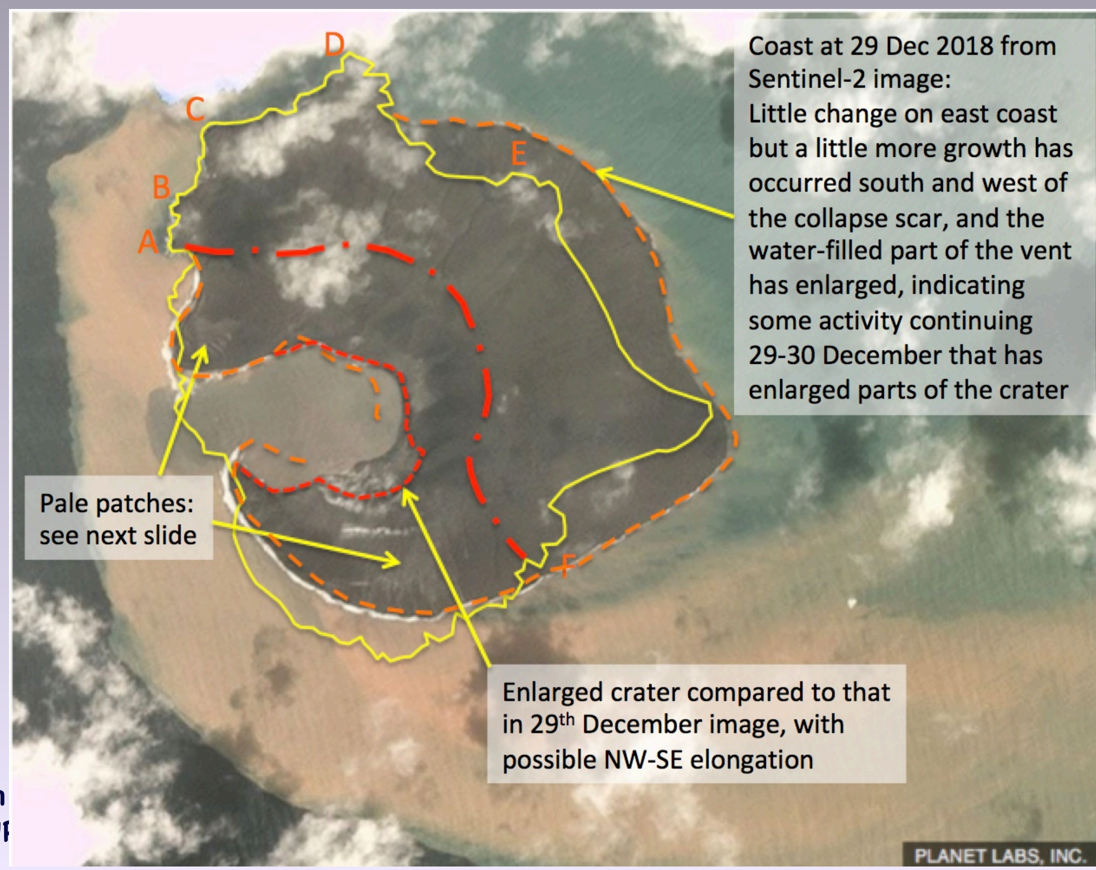
(iii) The position of the Surtseyan explosions in the Sidiq photos from the 23rd

Its position also coincides with that of the pre-collapse summit crater

Anak Krakatau 2018

-> Sector flank collapse of Anak Krakatau (radar, satellite images, video/drones,…) + subsequent Surtseyan phreatomagmatic activity

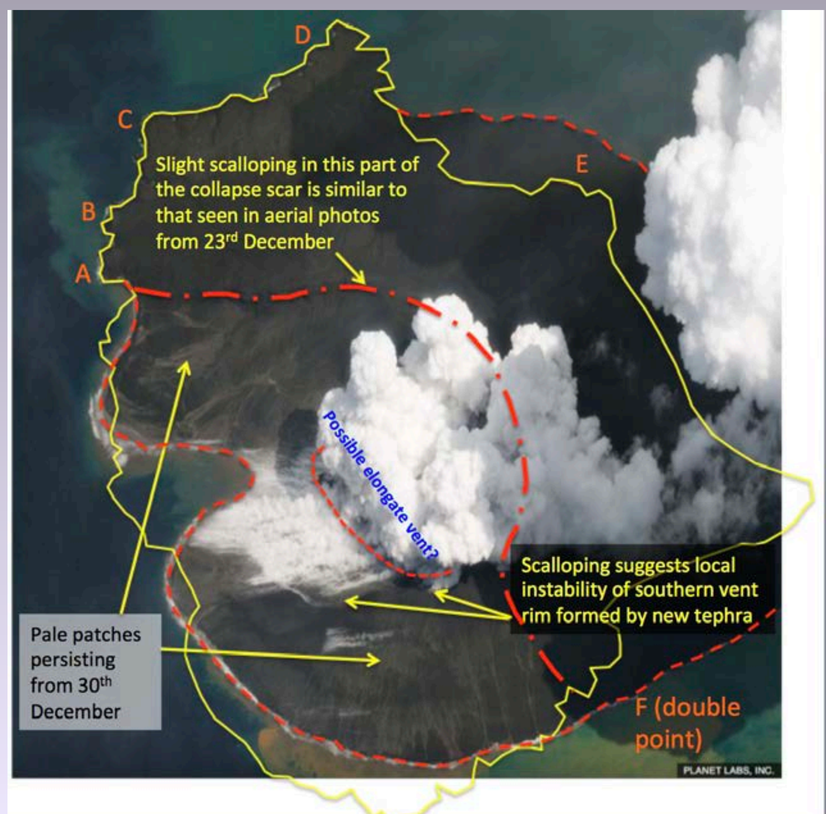
- Planet Lab image on Dec. 30th

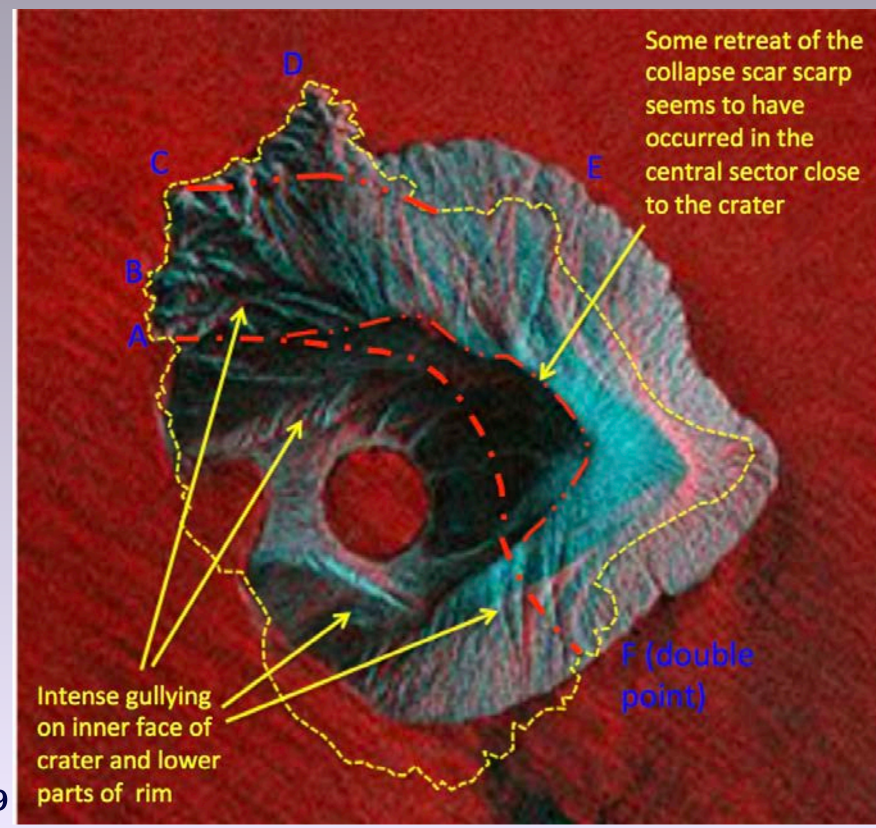


Anak Krakatau 2018

-> Sector flank collapse of Anak Krakatau (radar, satellite images, video/drones,...) + subsequent Surtseyan phreatomagmatic activity

- Jan. 2^{n} PL image, Jan. 9th Iceye radar => evolves then stabilizes





Anak Krakatau 2018

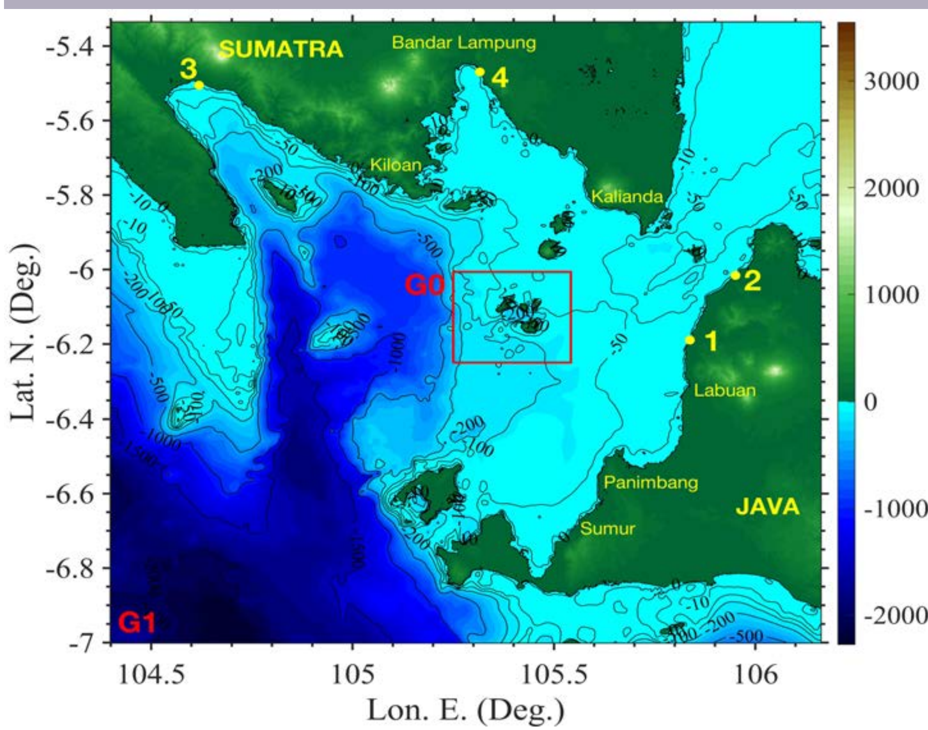
-> Sector flank collapse of Anak Krakatau (radar, satellite images, video/drones,…) + subsequent Surtseyan phreatomagmatic activity

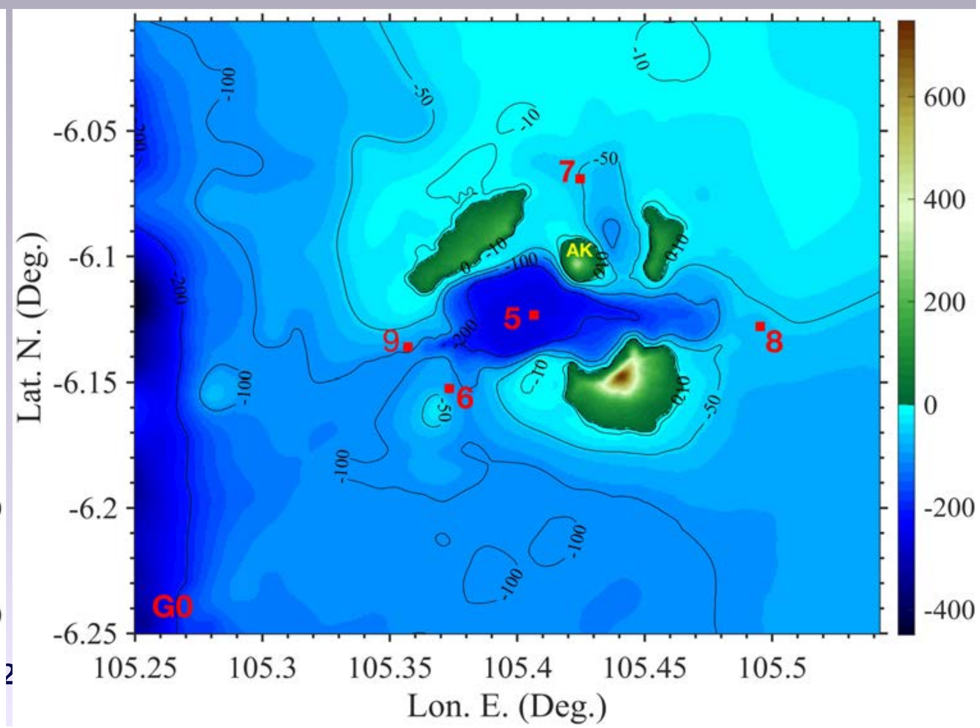
- Jan. 11th (Reynolds) => AK has stabilized

Anak Krakatau 2018

-> AK collapse geometric model:

- Build a pre-collapse bathymetry-topography (using Giachetti et al.'s (2012) 100 m res. data)
- Grid G0 (90x90m x5 layers) for NHWAVE model
- Grid G1 (100x100m) for FUNWAVE model



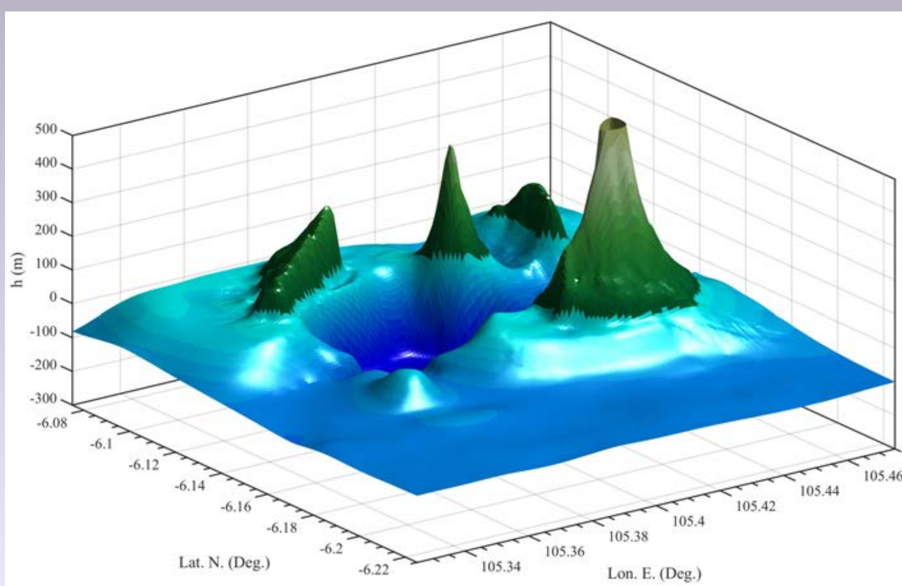


Anak Krakatau 2018

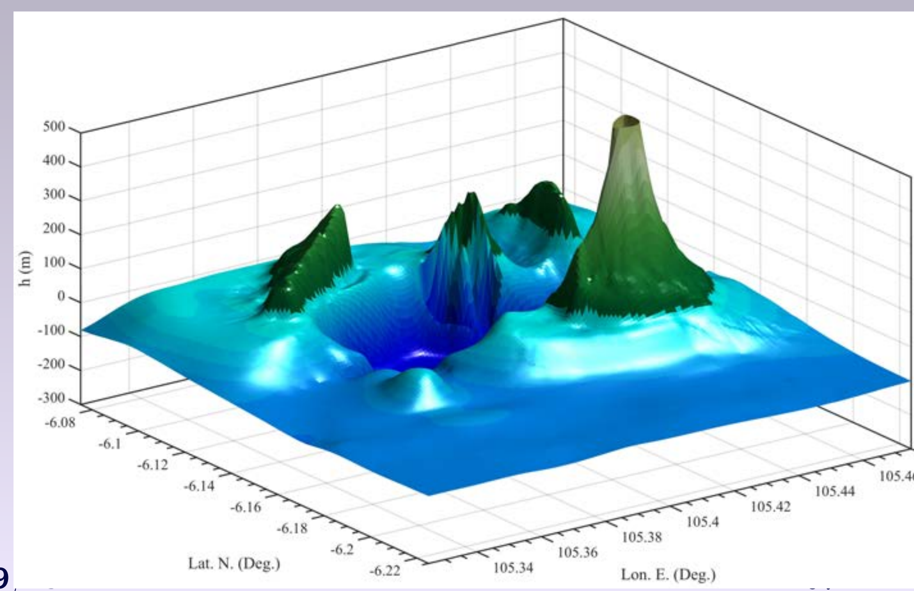
-> AK collapse geometric model:

- Build a pre-collapse bathymetry-topography (using Giachetti et al.'s (2012) 100 m res. data)
- Grid G0 (90x90m x5 layers) for NHWAVE model
- Create collapse volume model based on data => 0.35 km^3 volume

Pre-collapse



Post-collapse



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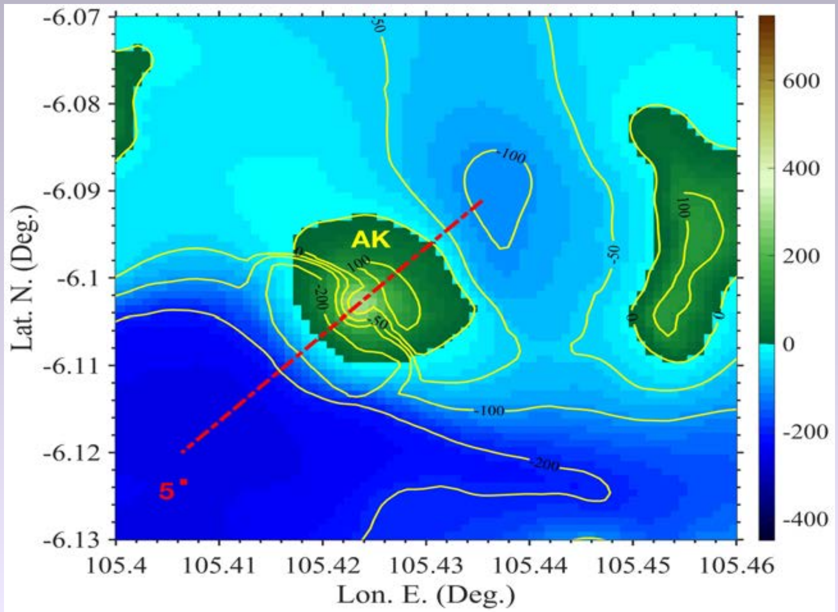
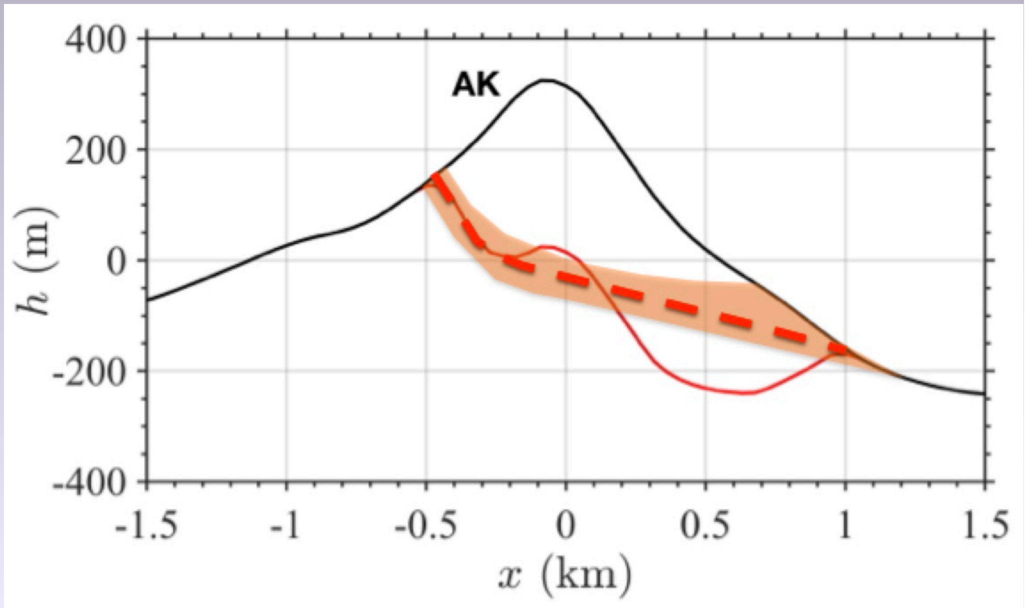
- Create collapse volume model based on data => 0.35 km^3 volume

Post-collapse (contours)



Post-collapse SW transect



Anak Krakatau 2018

-> AK 3D slide-tsunami generation:

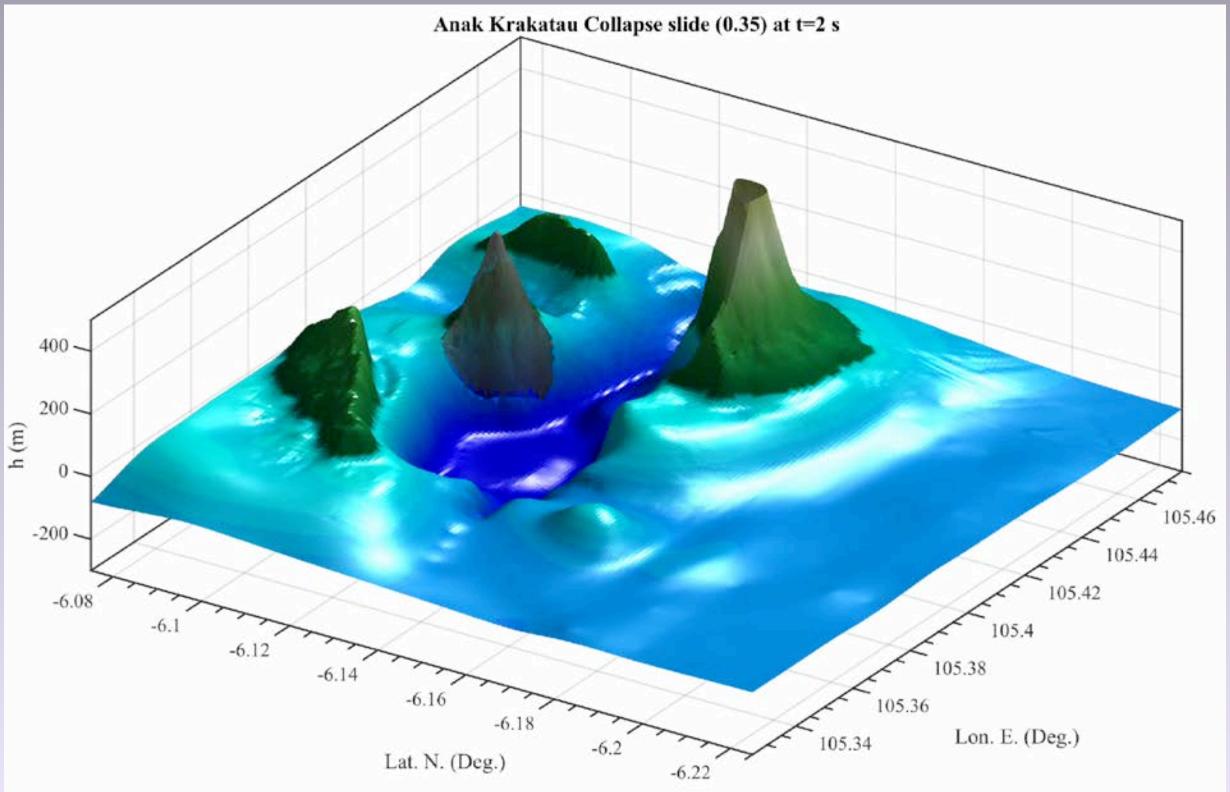
- Apply NHWAVE in Grid G0 (deforming bottom slide layer):
  - for dense viscous slide layer (Kirby et al., 2016; Cheng et al., 2018)

  - slide without water:

    ρ = 1900 kg/m^3

    ν = 0.5 m^2/s

    V_s = 0.35 km^3



Anak Krakatau 2018

-> AK 3D slide-tsunami generation:

- Apply NHWAVE in Grid G0 (deforming bottom slide layer):
  - for granular slide layer (Ma et al., 2015; Cheng et al., 2018)

  - slide without water:

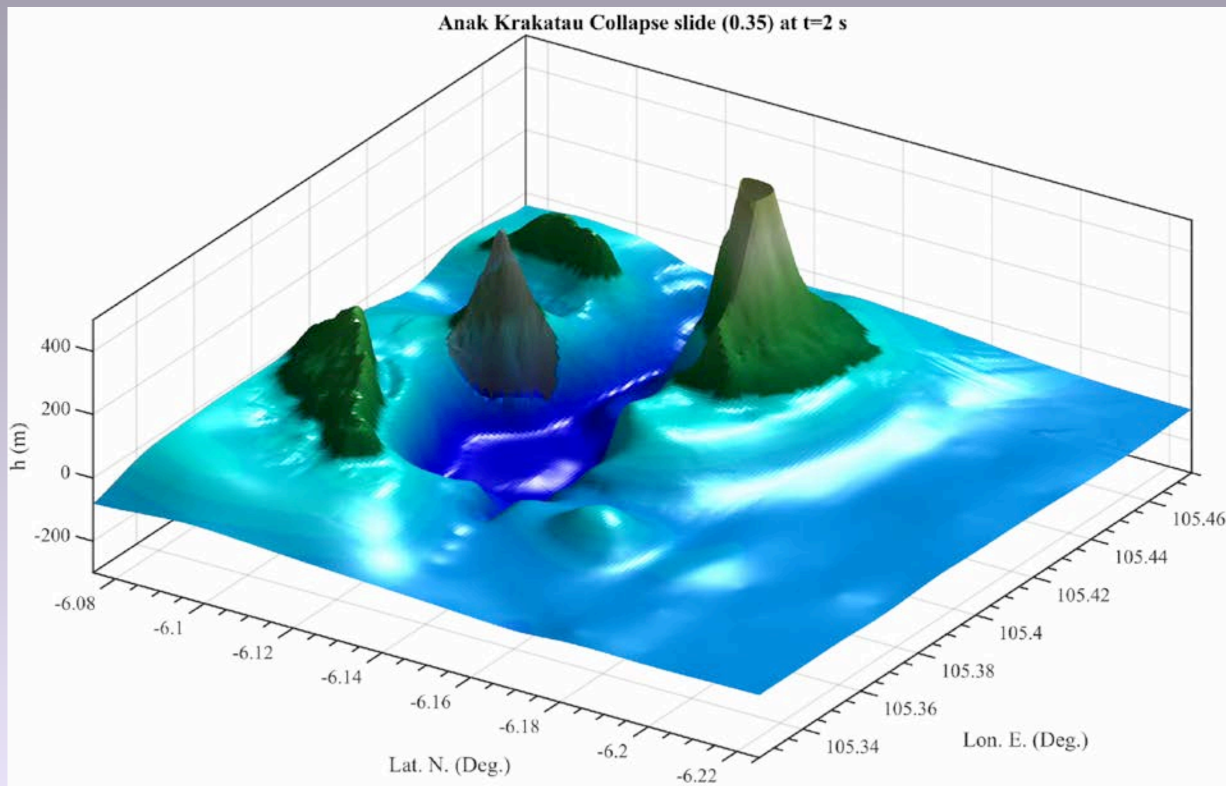
    ρ_m = 1550 kg/m^3

    ϕ_i = 10^o (intern. fr.)

    ϕ_b = 2^o (basal. fr.)

    p = 40%

    V_s = 0.35 km^3



Anak Krakatau 2018

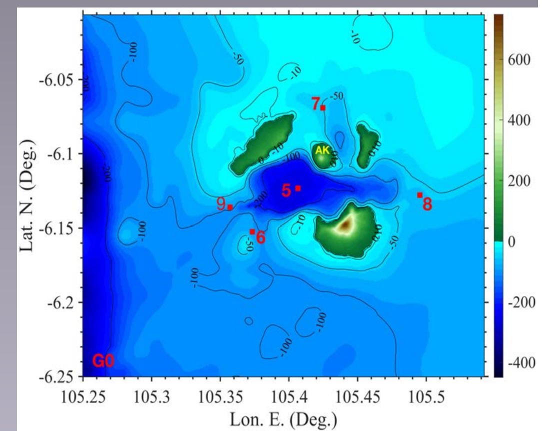
-> AK 3D slide-tsunami generation:

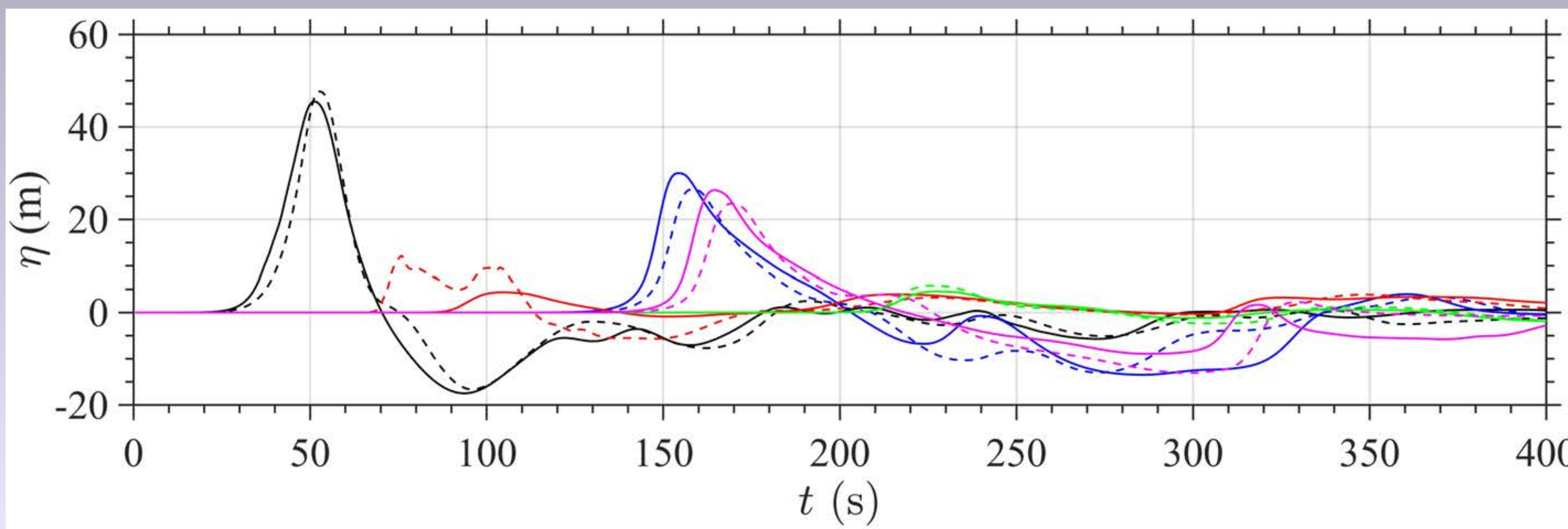
- Apply NHWAVE in Grid G0 (deforming bottom slide layer):
  - for dense viscous slide layer => tsunami generation

Anak Krakatau 2018

-> AK 3D slide-tsunami generation:

- Apply NHWAVE in Grid G0:
  - Surface elevation time series at wave gauge: (black) 5, (blue) 6, (red) 7, (green) 8, (magenta) 9, for (solid) viscous; (dashed) granular slide



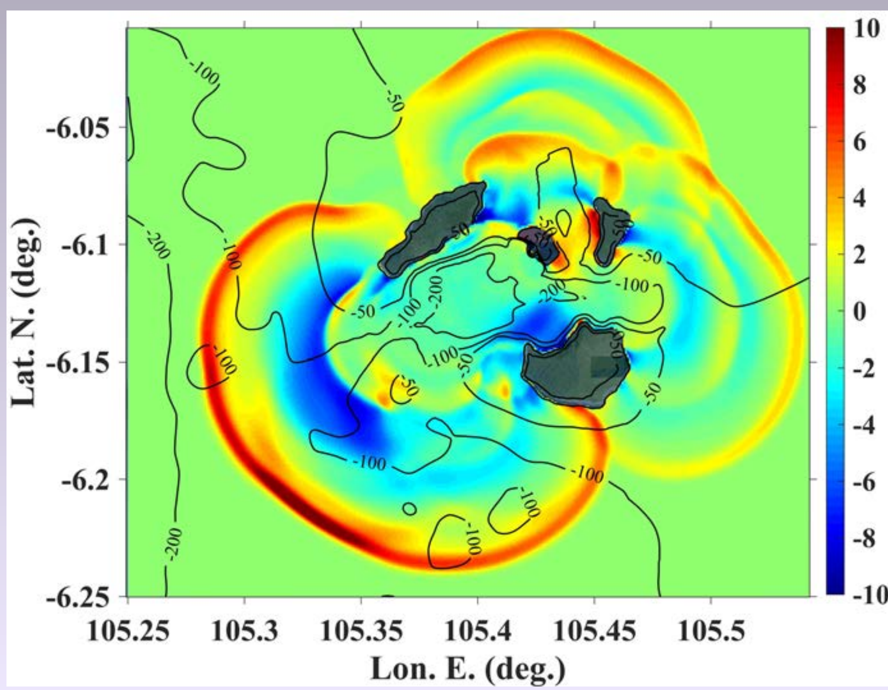


Anak Krakatau 2018

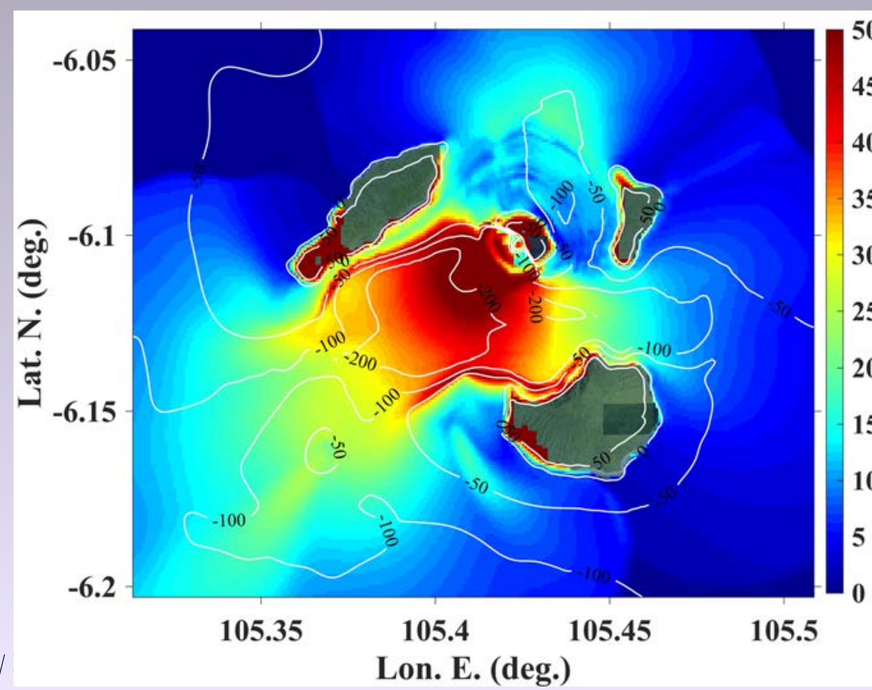
-> AK 3D slide-tsunami generation:

- Apply NHWAVE in Grid G0:
  - for dense viscous slide layer
  - Surface elevations:

Instantaneous (410 s)



Maximum (up to 410 s)

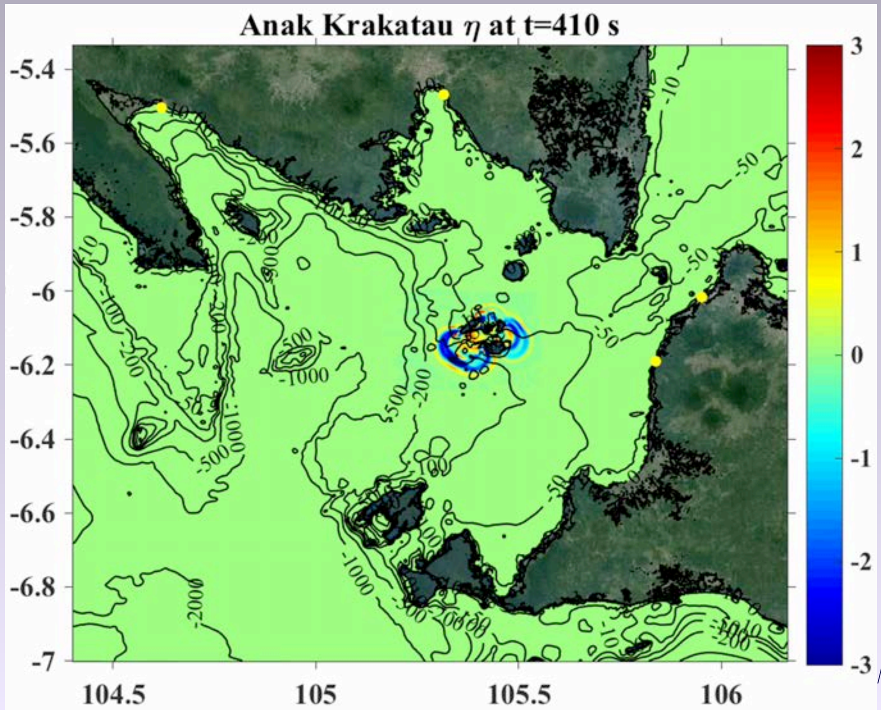


Anak Krakatau 2018

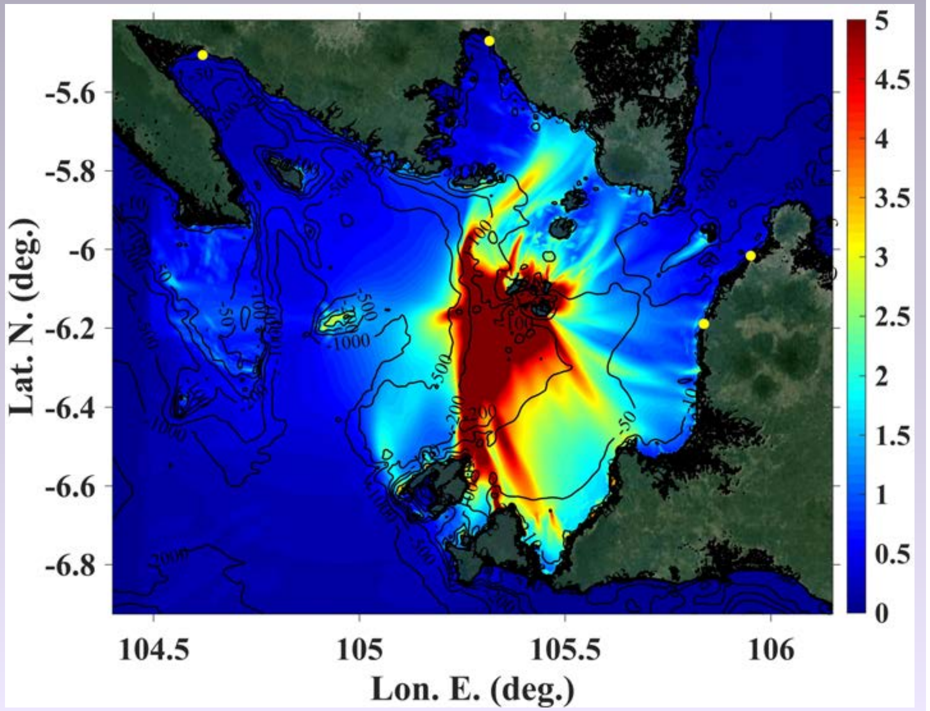
-> AK 2D slide-tsunami propagation/coastal impact:

- Initialize/run FUNWAVE in Grid G1 with NHWAVE results of grid G0
  - for dense viscous slide layer
  - Using surface elevations and horizontal velocities ($z = -0.531h$) at 410 s:

Instantaneous (from 410s)



Maximum (up to 7610 s)



Anak Krakatau 2018

-> AK 2D slide-tsunami propagation/coastal impact:

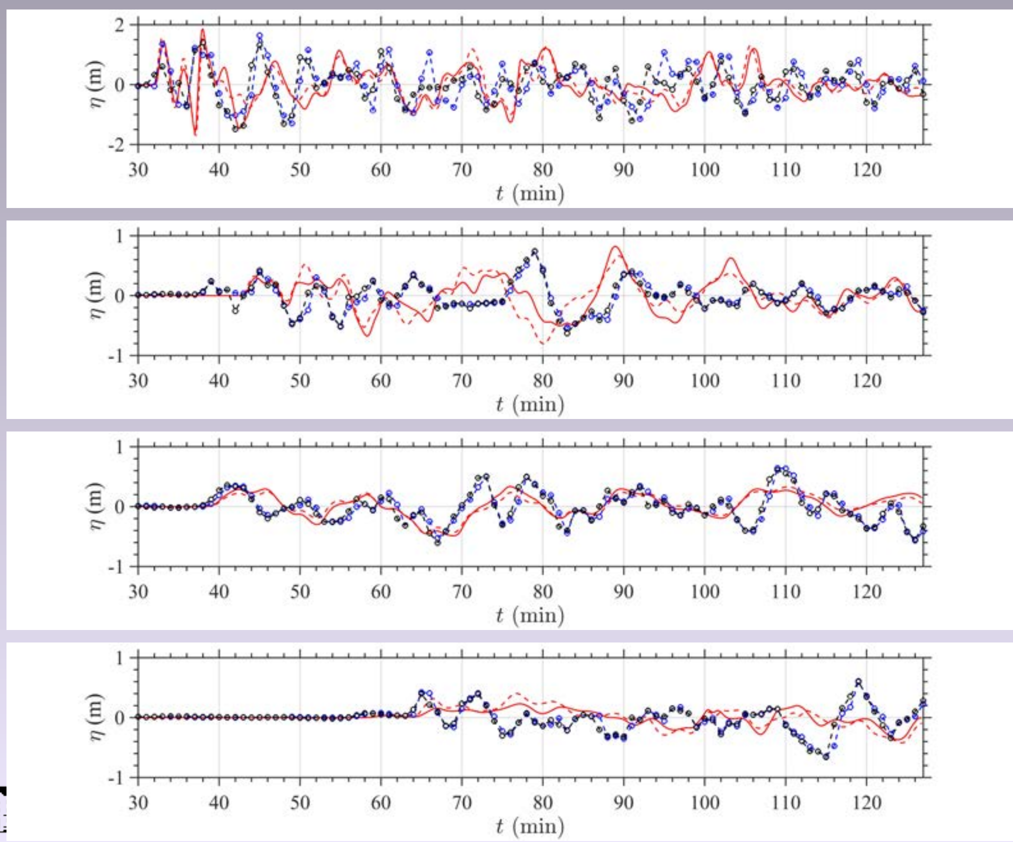
- Surface elevation time series for (solid) viscous; (dashed) granular slide at tide gauge:

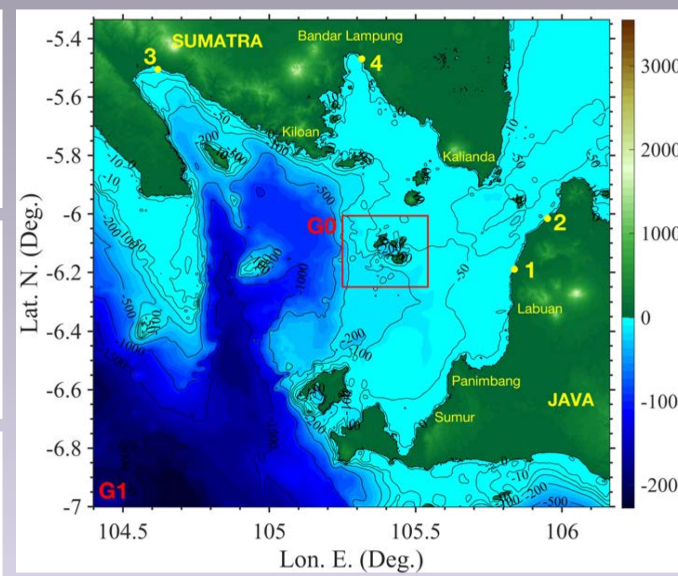
1

2

3

4



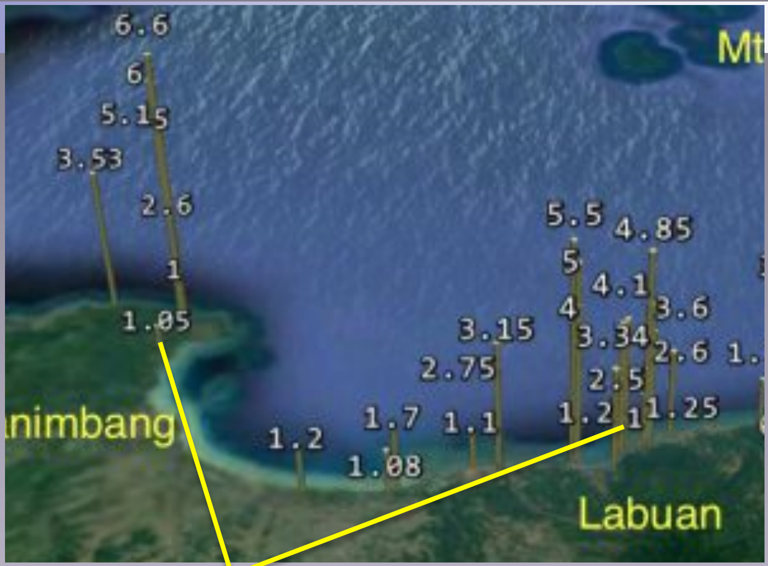


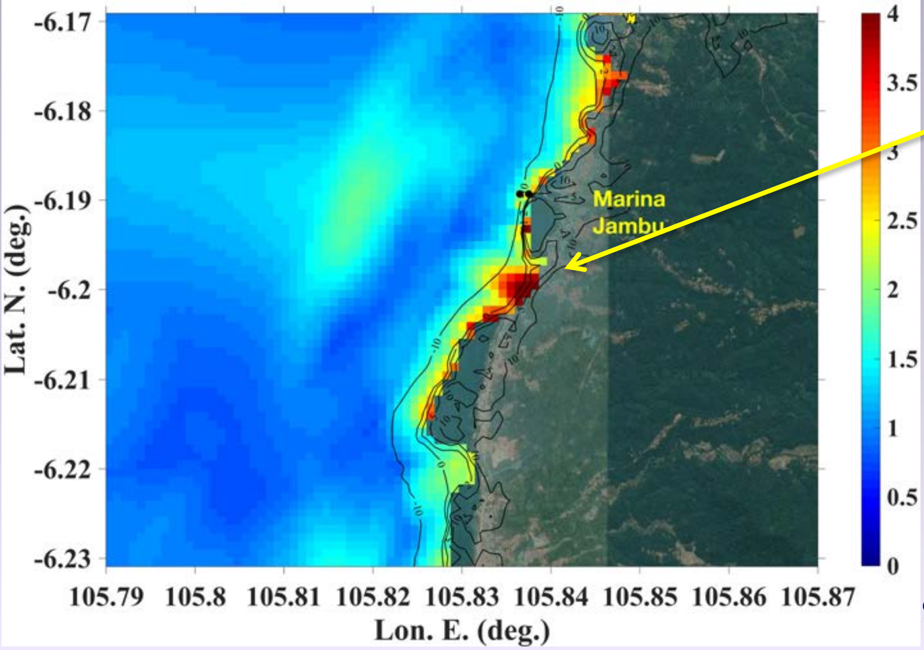
- Good agreement on arrival times
- Reasonable on heights

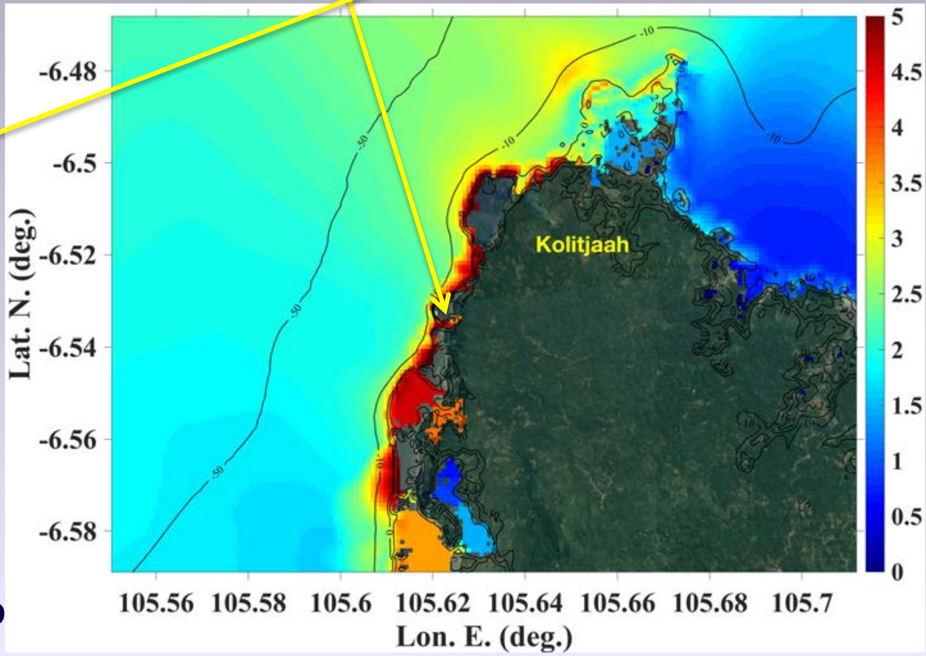
Anak Krakatau 2018

-> AK 2D slide-tsunami propagation/ coastal impact:

- Maximum surface elevations at the coast (viscous slide)



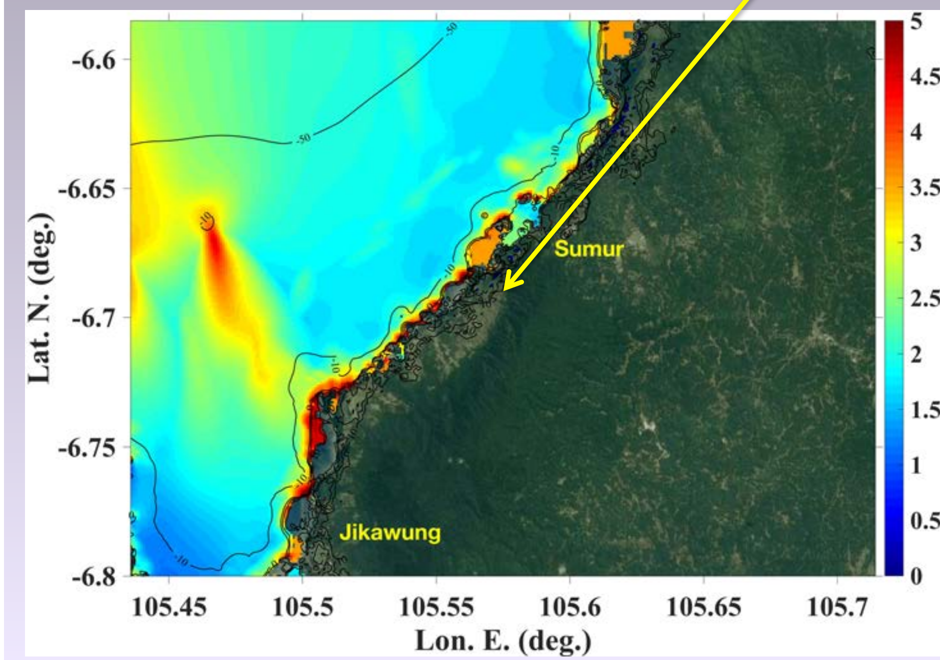


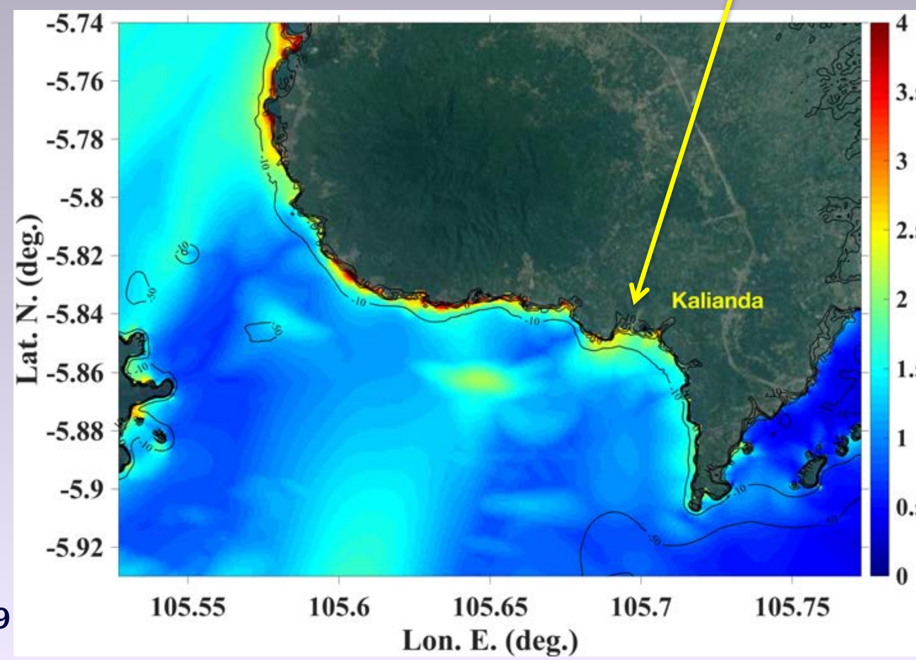


Anak Krakatau 2018

-> AK 2D slide-tsunami Propagation/ coastal impact:

- Maximum surface elevations at the coast (viscous slide)

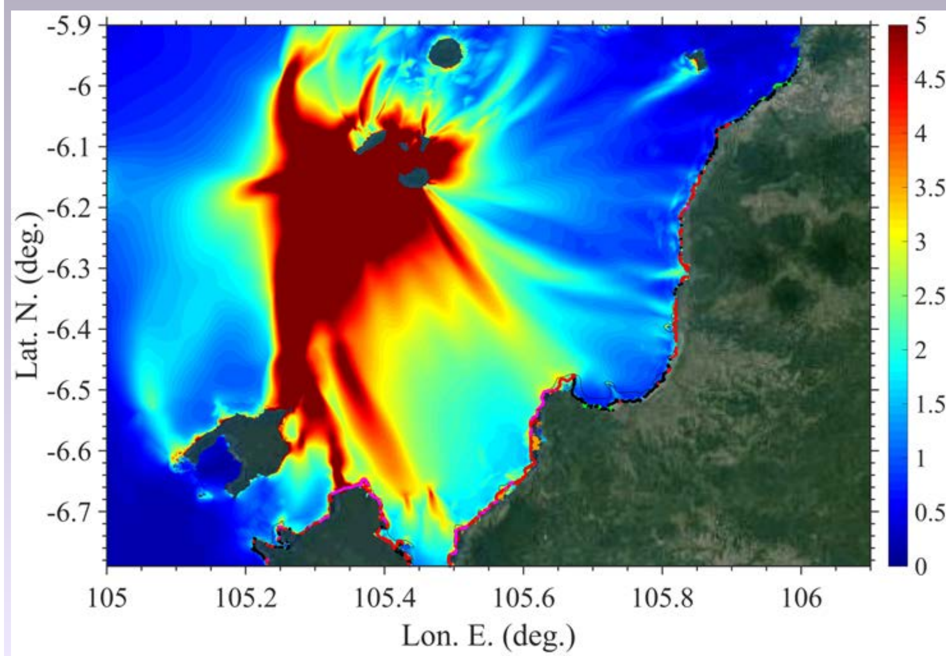


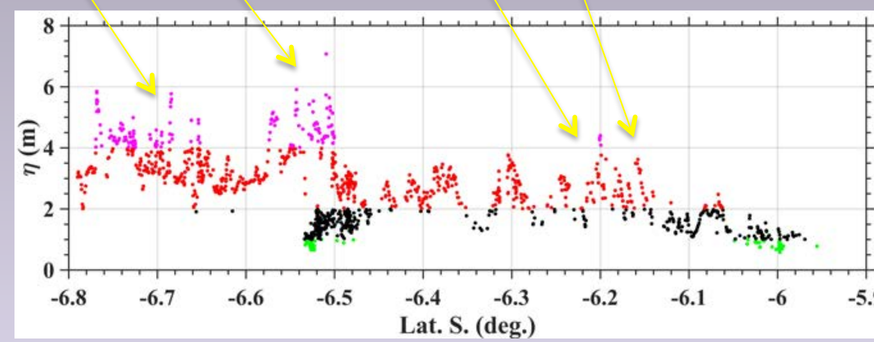


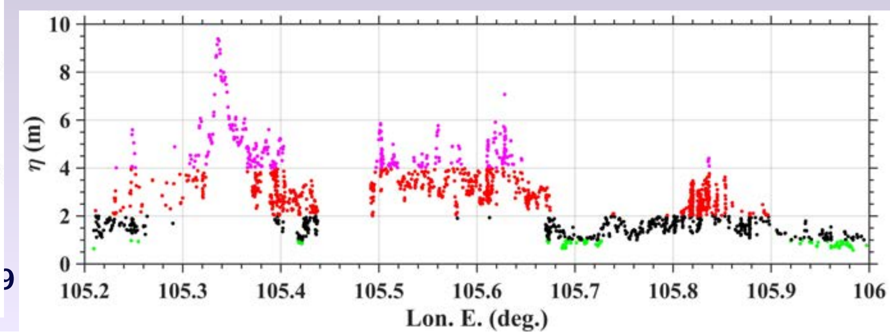
Anak Krakatau 2018

-> AK 2D slide-tsunami Propagation/ coastal impact:

- Maximum flow depth at the coast (viscous slide)



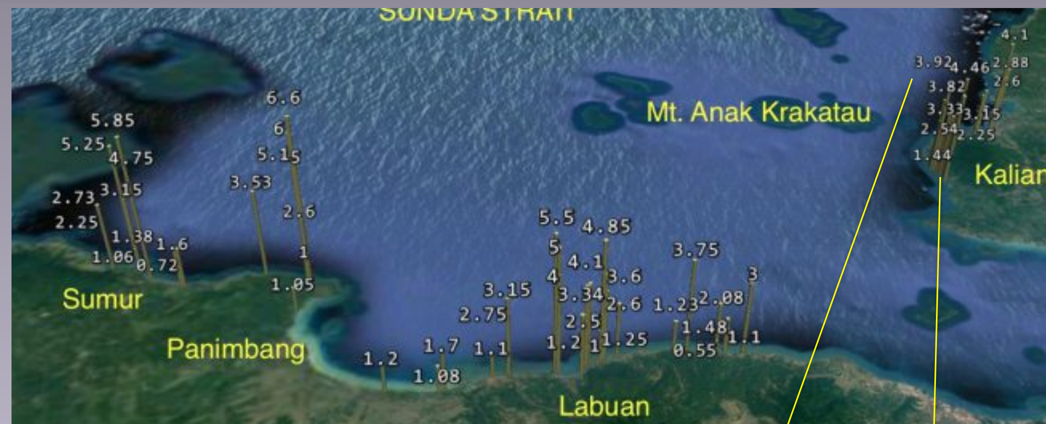


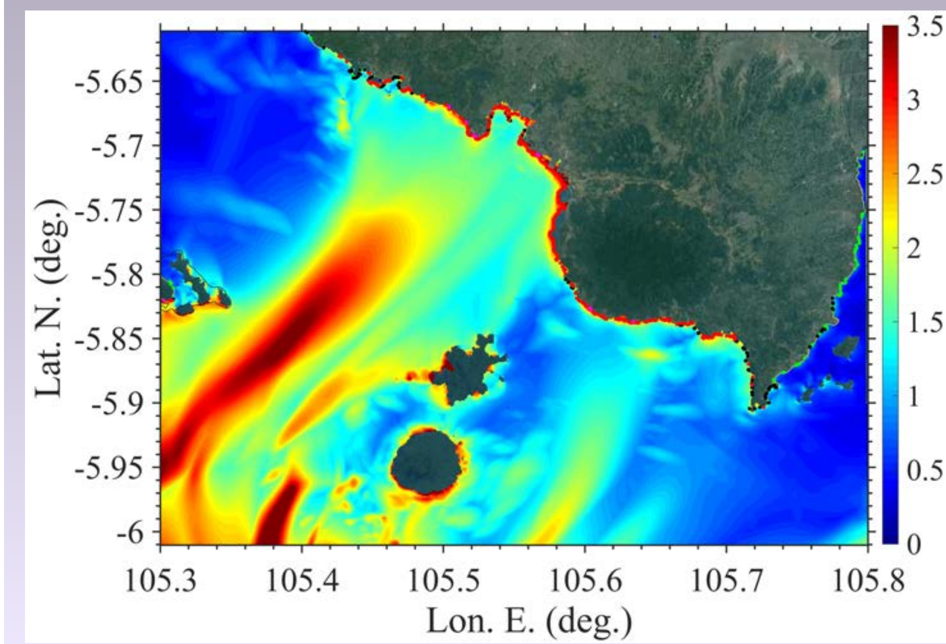


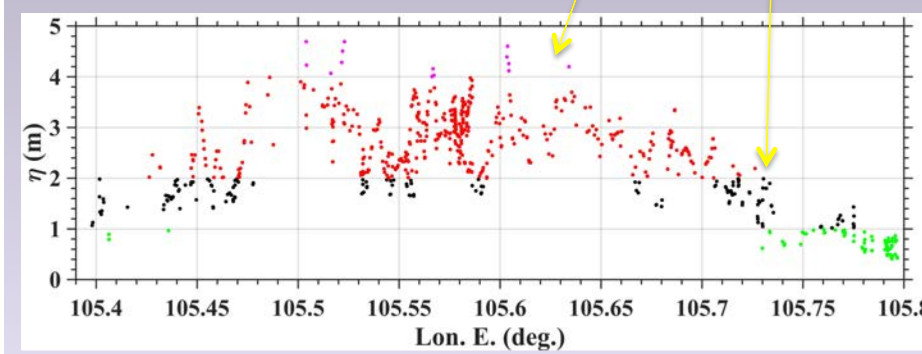
Anak Krakatau 2018

-> AK 2D slide-tsunami Propagation/ coastal impact:

- Maximum flow depth at the coast (viscous slide)



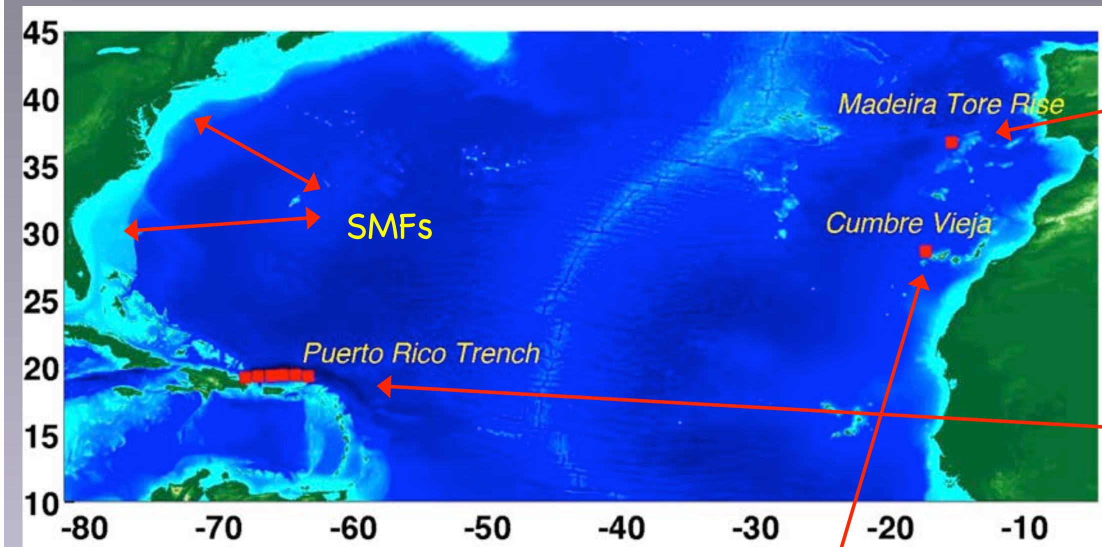




Anak Krakatau 2018

-> Erupting AK drone footage on 01/12/2019

Example : Tsunami sources for NTHMP US East Coast



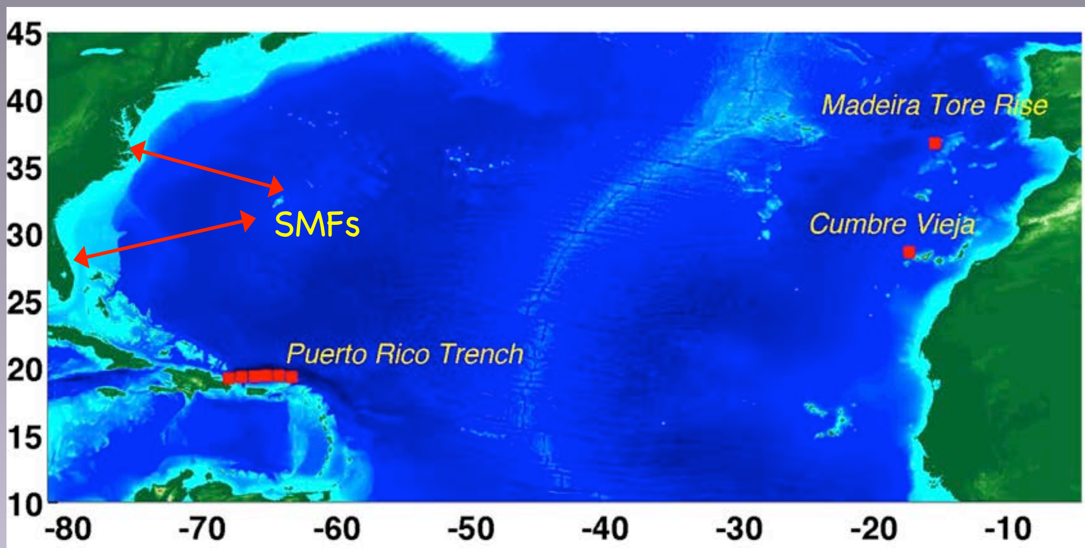
-> **LSB-M9** far-field *seismic source* : repeat of Lisbon 1755 [Barkan et al., 2008]

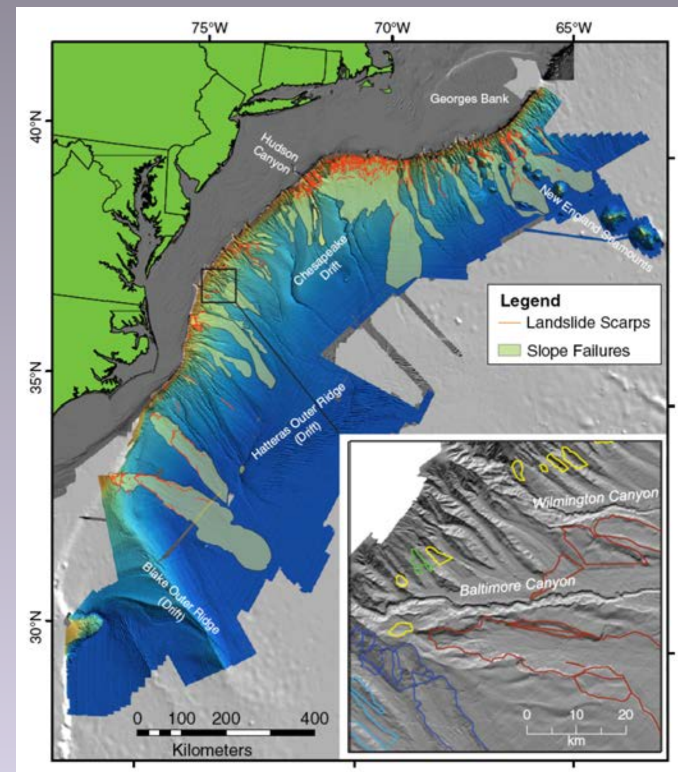
-> **PRT-M9** far-field *seismic source* in PRT: 600 x 150 km (12 SIFT sources; 12 m slip; 600 yr of full convergence)
[Knight, 2006; Grilli et al., 2010; NHESS]

-> **CVV** Far-field *flank collapse* of CVV (80 to 450 km^3 volume; return period (?) perhaps 1,000-100,000 yrs.

-> near-field **SMFs** on continental slope/margin: assumed to be rigid slumps with Currituck slide characteristics (***proxies***; 155 km^3)

Example : Tsunami sources for NTHMP US East Coast





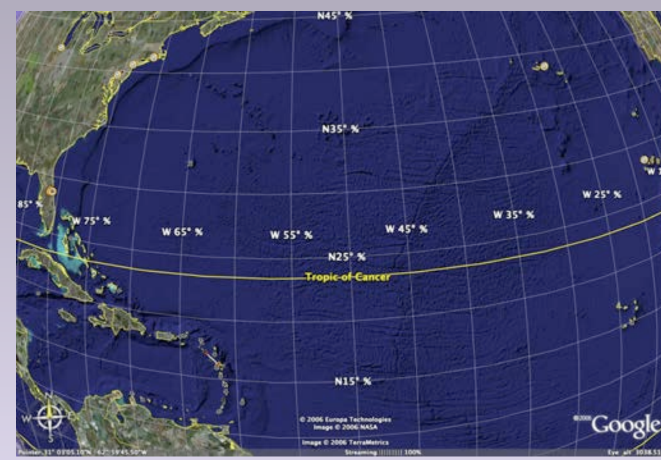
[Ten Brink et al (2014)]

-> SMF triggered by earthquakes or not can generate large damaging tsunamis

-> SMF scars are widespread on US Atlantic margin, but mostly old 1,000s of yrs. But see 1929 Grand Bank SMF tsunamis

Case study: Cumbre Vieja/La Palma Flank Collapse

[Ward and Day (2001); Grilli et al., (2005); Pérignon (2006); Lovholt et al., 2008; Abadie et al. (2008-2012)]

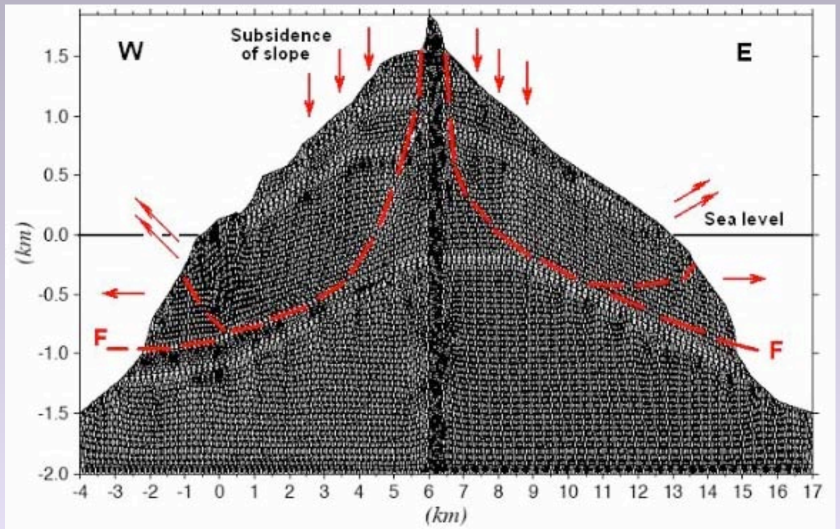


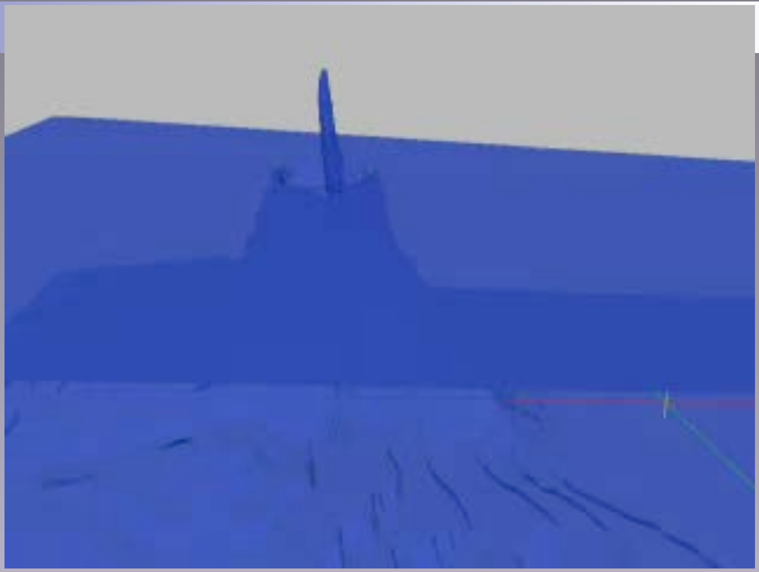
Case study: Cumbre Vieja Flank Collapse

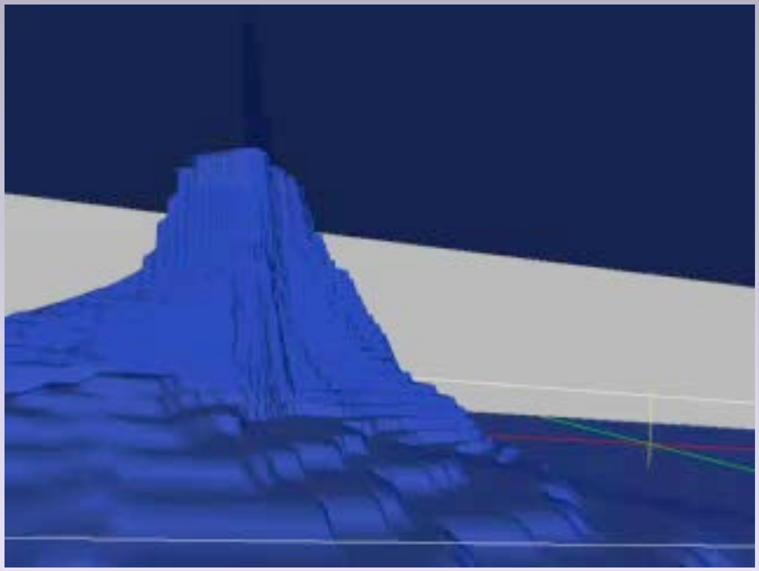
- Multi-fluids 3D-Navier Stokes-VOF model (THETIS) (Abadie et al.; 2006-11)
- Slope stability analysis (FLAC 2D; 2D-FEM)

-> Most likely scenario of 80 km^3

- Various scenario simulated with 20-450 km^3. Large 3D grids.







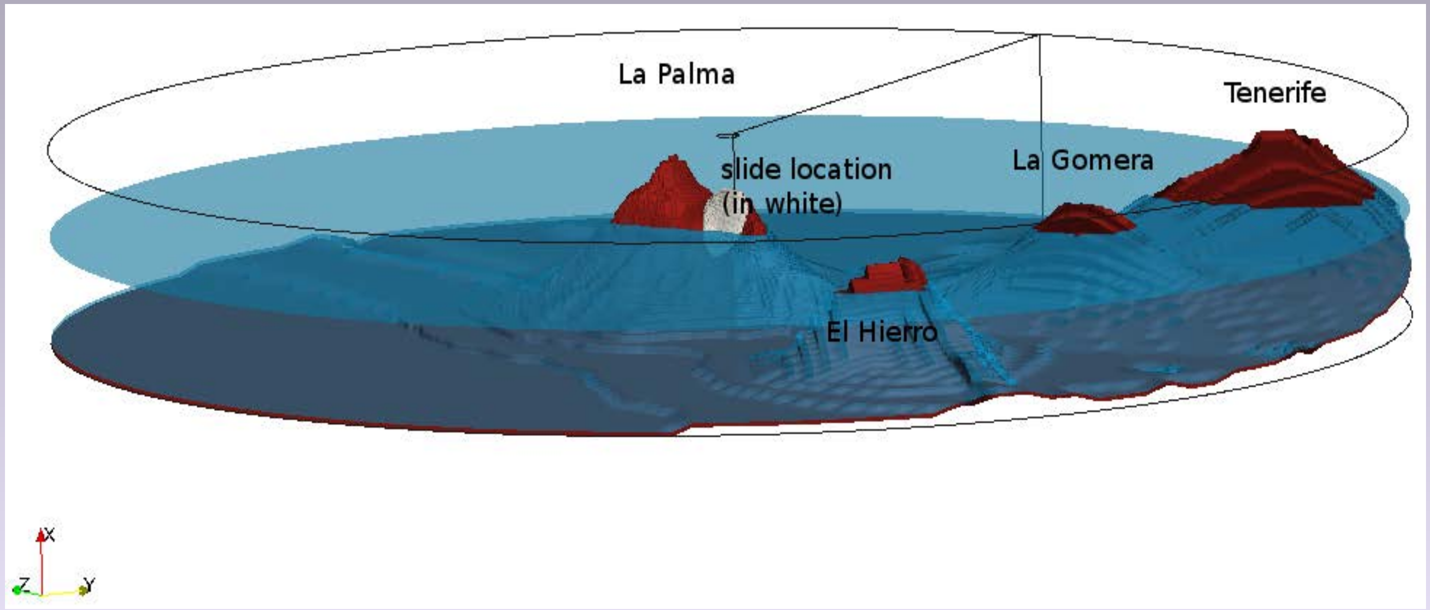
[U. of Bordeaux]

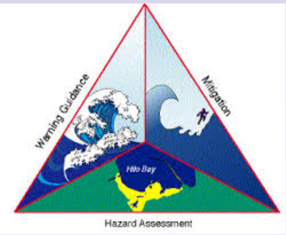
Case study: CVV Flank Collapse

- Source + near-field propagation : Multi-fluids 3D-NS-VOF model (THETIS)

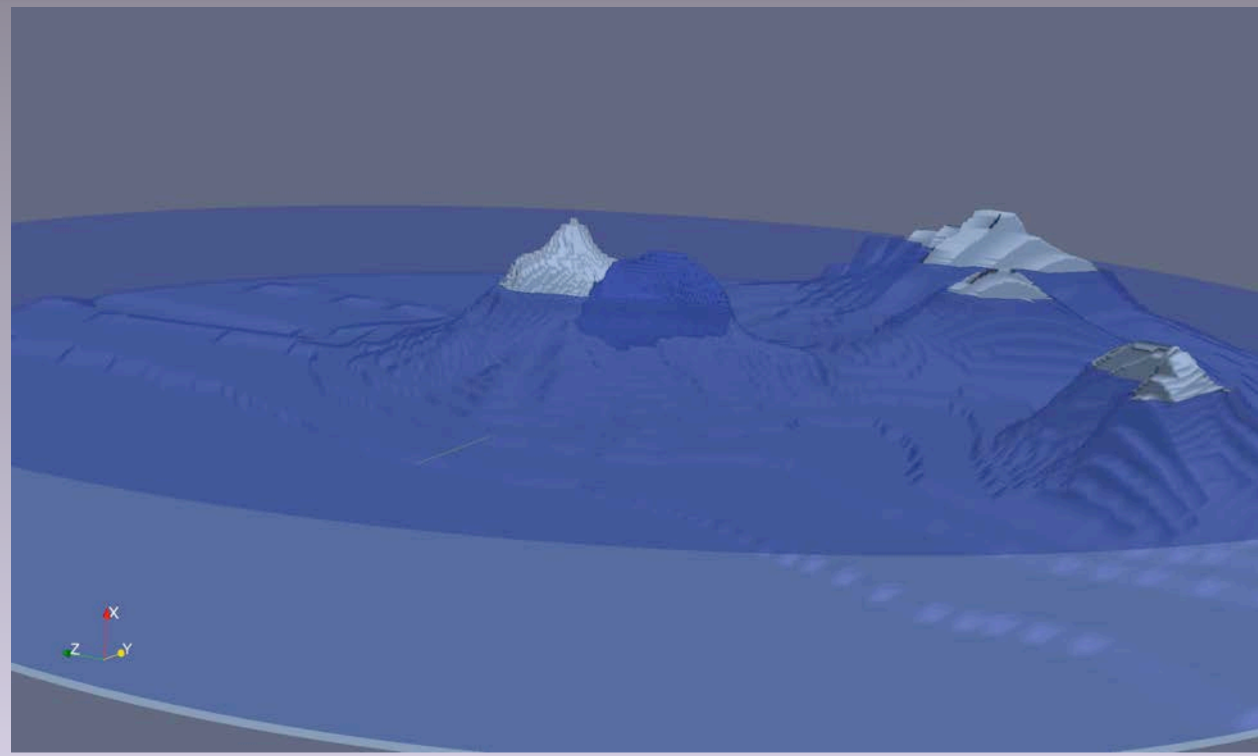
For lack of better information, slide is assumed to behave as an inviscid fluid with constant density => worst case scenario.

- If known, an arbitrary rheology can be used.

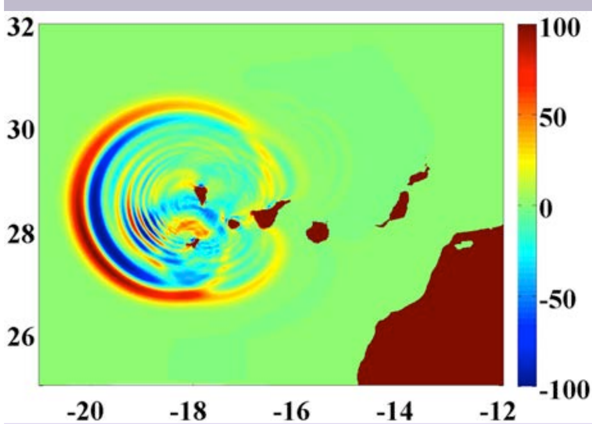


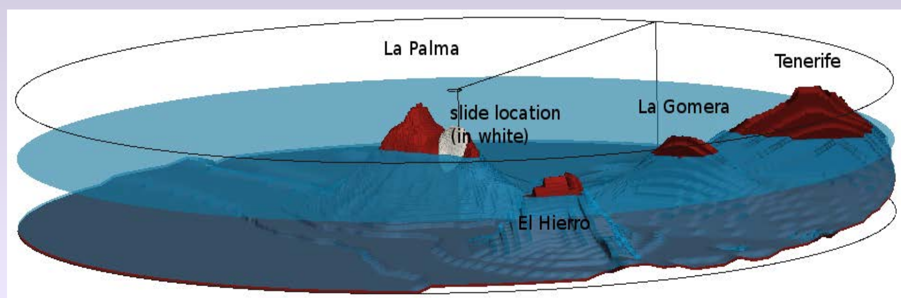


CVV Flank Collapse source (450 km^3)



-> 3D simulation
up to 20 min



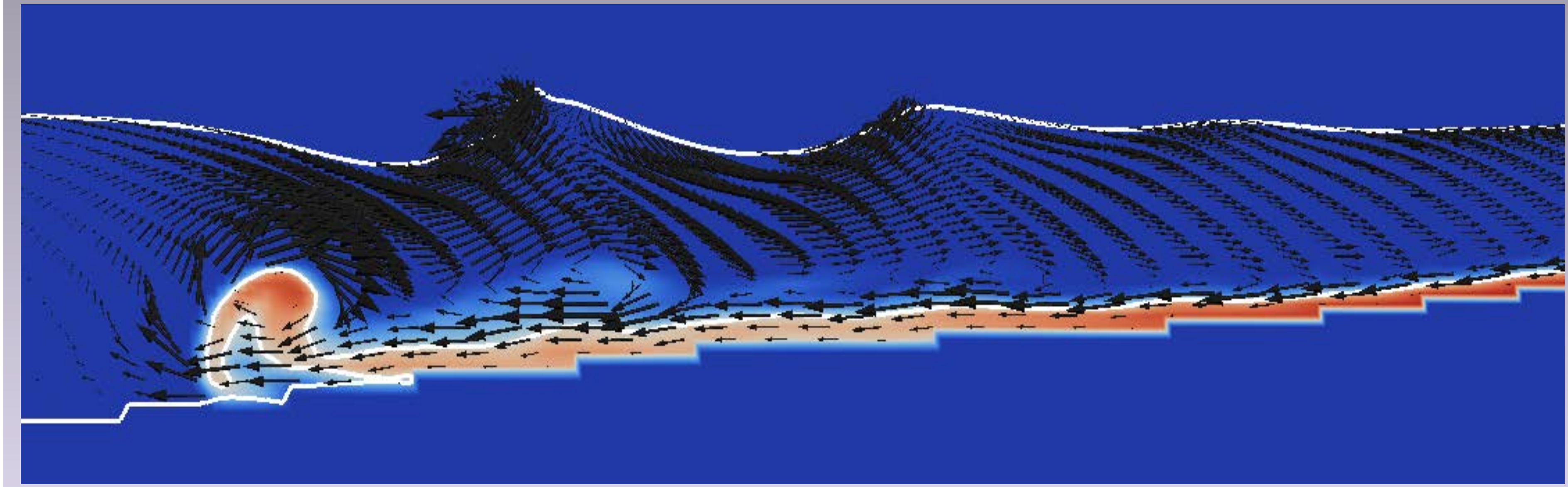


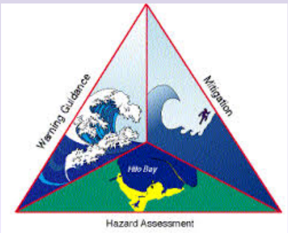
Dept. of Ocean
Engineering, URI

CVV Flank Collapse : 2D sensitivity analysis

- Source + near-field propagation : THETIS 80 km^3 CVV source :

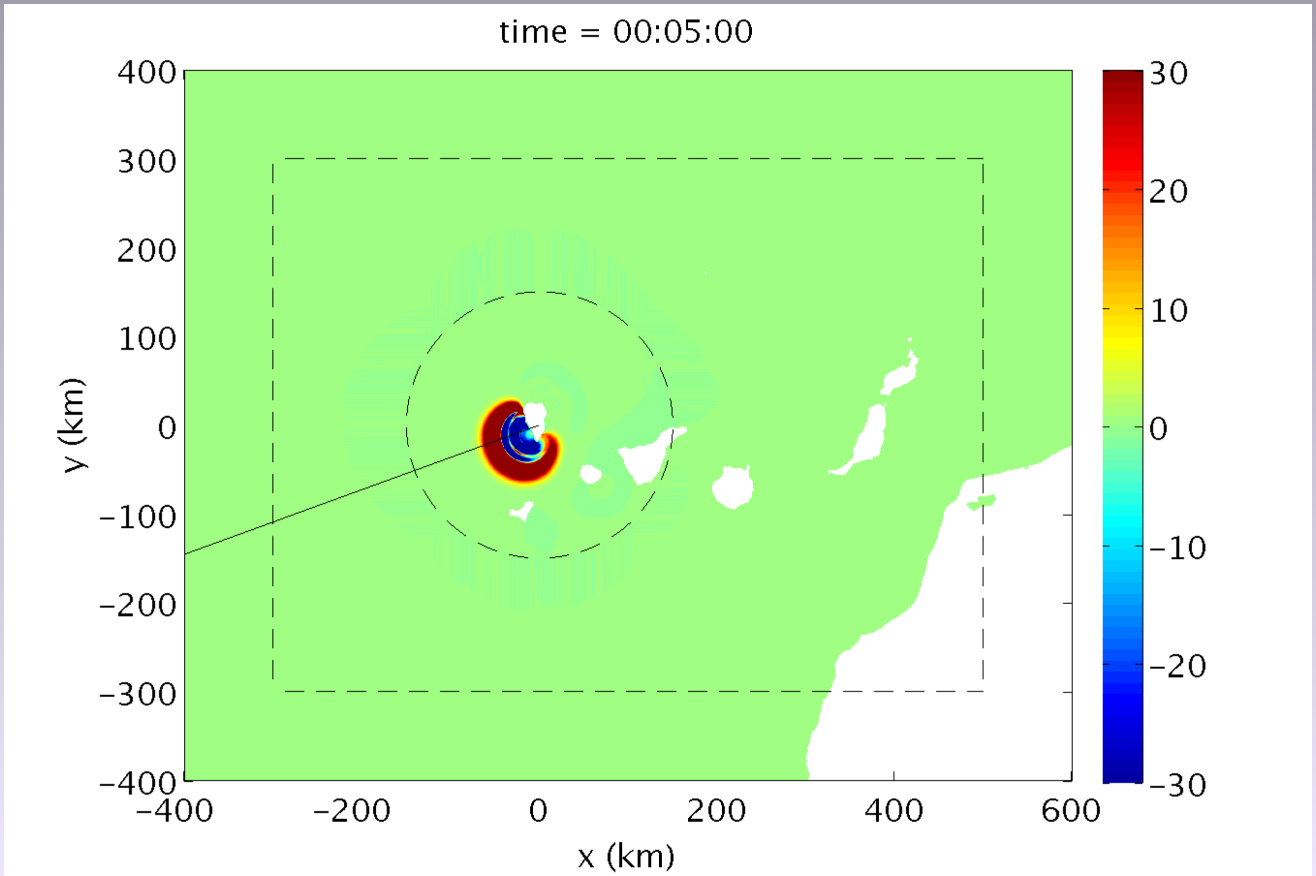
Detailed velocity field around slide tip at t = 396 s.



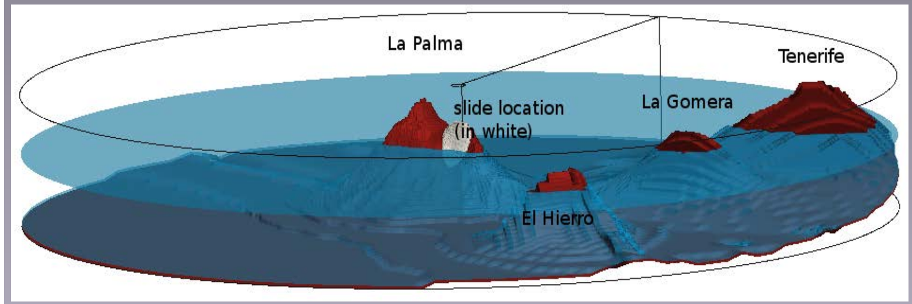


Case study: CVV Flank Collapse

- Regional/Transoceanic/East coast propagation : 2D-horiz Fully Nonlinear Boussinesq model FUNWAVE in various nested grids (80 km^3 CVV source)

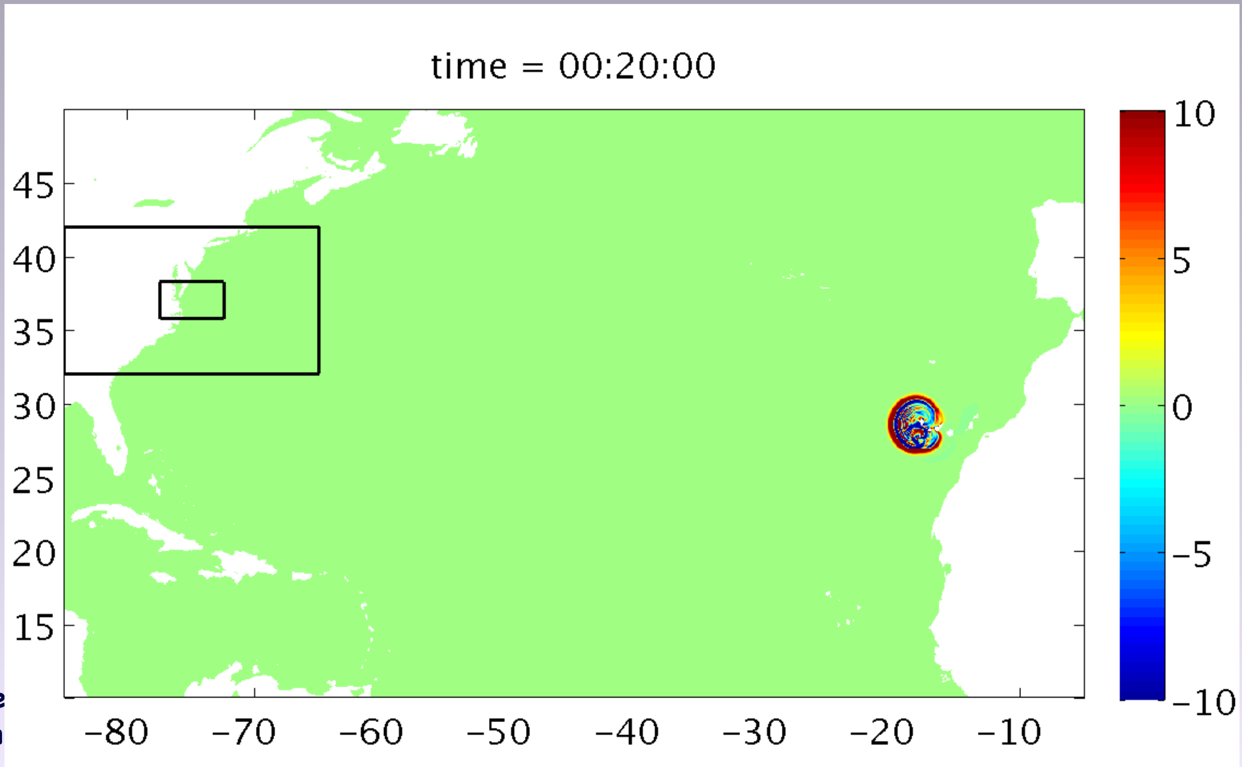


CVV Flank Collapse source (450 km³)



-> 2D-FUNWAVE transoceanic nested grids

-> Surface elevation as a fct of time (m)



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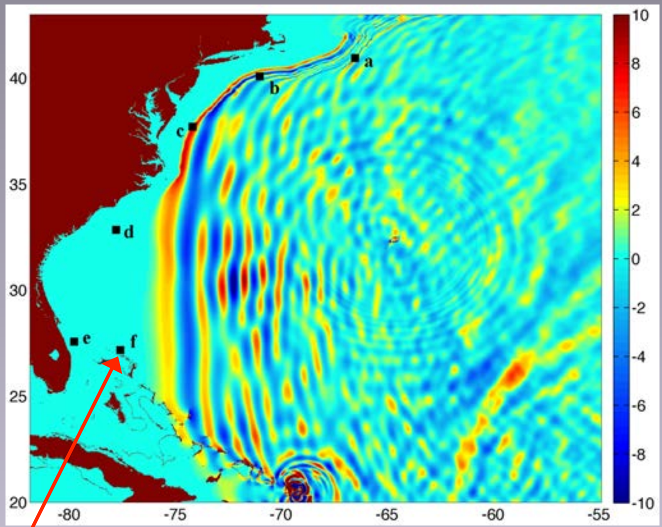
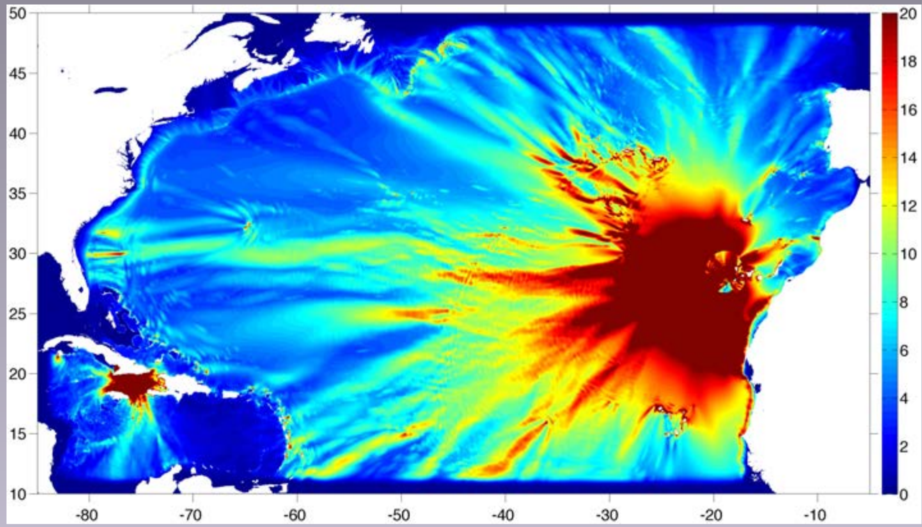
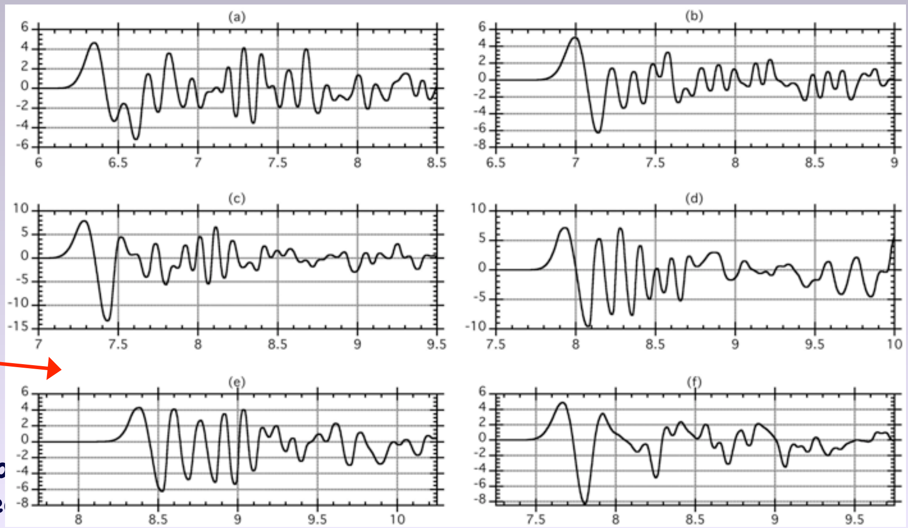
CVV Flank Collapse source (450 km^3)







-> Dispersive trains of large waves, 9-12 min period (200 m gauge)

-> 450 km^3:
5-6 m runup/inundation
-> 80 km^3:
2-2.5 m runup/inundation

Dept. o
Engine

Thank you